U. S. NAVAL PROVING GROUND
DAHLGREN, VIRGINIA

REPORT NO. 14-45

# FIRST PARTIAL REPORT ON ALUMINUM ALLOY ARMOR.

PART I



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# FIRST PARTIAL REPORT ON ALUMINUM ALLOY ARMOR

## PART I



## PART II

## LIST OF FIGURES

## LIST OF TABLES

## ABSTRACT

This first partial report on the use of aluminum alloys as armor, presents a discussion of the various technical aspects of aluminum production and, in addition, reports the results of metallurgical and ballistic investigations of a series of alloys submitted by the Aluminum Company of America. It has been found that the penetration resistance of aluminum alloys can be correlated with Brinell hardness and that the shock resistance can be evaluated on the basis of the tensile impact properties. In addition, the effects of cladding and of reduction during rolling upon the ballistic performance of aluminum alloys have been determined.

# I. INTRODUCTION TO THE METALLURGY OF ALUMINUM.

## Aluminum and Alloys of Aluminum

Aluminum is produced by an electrolytic extraction process discovered only a little more than fifty years ago. By this method the aluminum ore, bauxite ($Al_2O_3 \cdot 3H_2O$) is purified by chemical leaching and then reduced electrolytically to commerical aluminum having a nominal purity of about 99.7%. This aluminum contains small amounts of iron and silicon and has a tensile strength about 50% higher than that of aluminum of high purity.

The principal characteristics of pure aluminum are low specific gravity and low strength. By the addition of small amounts of copper, silicon, manganese, magnesium, and zinc followed by suitable heat treatment, the strength of aluminum may be increased 7-8 fold with an increase in specific gravity which seldom exceeds 3%. The ease with which desirable properties can be obtained in aluminum alloys has been the most important factor in the spectacular development of the aluminum industry. "Aluminum", in the popular sense, includes all aluminum alloys in which aluminum is the principal constituent.

The alloying elements may be added to aluminum either singly or in combination depending on the characteristics desired in the resulting alloys. In the alloys which are to be rolled or forged, "Wrought Alloys", the total percentage of alloying elements is usually kept below 7%. "Casting Alloys" which are not subjected to shaping by forging or rolling, usually contain appreciably higher percentages of alloying elements. "Wrought Alloys" and "Casting Alloys" are of two types: in one, improvement by heat treatment is not possible; in the other, heat treatment is used to affect the major part of the improvement obtained. Hence, both wrought alloys and casting alloys are further classified as heat treatable and non heat treatable alloys according to the nature and quantity of the specific alloying additions which form the basis for these classifications. Tables I and II list the nominal compositions of typical wrought and casting alloys. Generally those alloys which contain one per cent copper or more are properly classed as heat treatable alloys.

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TABLE II

NOMINAL COMPOSITIONS OF ALUMINUM CASTING ALLOYS

| | ALLOY | %Cu | %Fe | %Si | %Mn | %Mg | %Zn | %Ni | %Al |
|---|---|---|---|---|---|---|---|---|---|
| ALCOA | 13 | | | 12.0 | | | | | Bal. |
| ALCOA | 43 | | | 5.0 | | | | | Bal. |
| ALCOA | 79 | 4.0 | | 7.0 | | | | | Bal. |
| ALCOA | 82 | 14.0 | | 5.0 | | | | | Bal. |
| ALCOA | 93 | 4.0 | | 2.0 | | | | 4.0 | Bal. |
| ALCOA | 112 | 7.0 | 1.2 | | | | 1.7 | | Bal. |
| ALCOA | A132 | 0.8 | 0.8 | 12.0 | | 1.0 | | 2.5 | Bal. |
| ALCOA | 218 | | | | | 8.0 | | | Bal. |
| ALCOA | 645 | 2.5 | 1.2 | | | | 11.0 | | Bal. |

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TABLE I

NOMINAL COMPOSITIONS* OF WROUGHT ALUMINUM ALLOYS

| | ALLOY | %Cu | %Si | %Mn | %Mg | %Zn | %Ni | %Cr | %Al |
|---|---|---|---|---|---|---|---|---|---|
| ALCOA | 2S | | | | | | | | 99.2 |
| ALCOA | 3S | | | 1.2 | | | | | Bal. |
| ALCOA | 11S | 5.5 | | | | | | | Bal. |
| ALCOA | 14S | 4.4 | 0.8 | 0.8 | 0.4 | | | | Bal. |
| ALCOA | 17S | 4.0 | | 0.5 | 0.5 | | | | Bal. |
| ALCOA | A17S | 2.5 | | | 0.3 | | | | Bal. |
| ALCOA | 18S | 4.0 | | | 0.5 | | 2.0 | | Bal. |
| ALCOA | 24S | 4.5 | | 0.6 | 1.5 | | | | Bal. |
| ALCOA | 25S | 4.5 | | 0.8 | 0.8 | | | | Bal. |
| ALCOA | 32S | 0.9 | 12.5 | | 1.0 | | 0.9 | | Bal. |
| ALCOA | A51S | | 1.0 | | 0.6 | | | 0.25 | Bal. |
| ALCOA | A52S | | | | 2.5 | | | 0.25 | Bal. |
| ALCOA | 53S | | | | 1.3 | | | 0.25 | Bal. |
| ALCOA | 56S | | | 0.1 | 5.2 | | | 0.10 | Bal. |
| ALCOA | 61S | 0.2 | 0.6 | | 1.0 | | | 0.25 | Bal. |
| ALCOA | 70S | 1.0 | | 0.7 | 0.4 | 10.0 | | | Bal. |
| ALCOA | 75S | 1.5 | | 0.2 | 2.5 | 6.0 | | 0.25 | Bal. |
| REYNOLDS | 301+ | 4.5 | 1.0 | 0.8 | 0.4 | | | | Bal. |
| REYNOLDS | 303+ | 1.5 | | .1 | 2.5 | 6.0 | | 0.20 | Bal. |

* It should be noted that 0.2% Si and 0.5% Fe is a normal content of commercial aluminum.

\+ The Reynolds Company does not use the letter "S" on these alloys.

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Aluminum alloys may have substantially the same tensile strength but differ widely in yield strength, ductility, in the ease with which they may be cast, heat treated, fabricated and in many other factors which may decide the choice of the material for specific applications. In general, it may be said that most aluminum alloys have been designed for very specific applications and are manufactured only in those forms for which they were designed.

Binary Alloys of Aluminum

The more common alloying elements of aluminum are copper, silicon, manganese, magnesium, and zinc. The characteristics of the binary alloys of these elements and aluminum are as follows:

Copper: The aluminum-copper alloys are the oldest and most widely used of all commercial alloys of aluminum. Alloys containing up to five per cent copper are easily rolled and are classed as wrought alloys; alloys containing up to fifteen per cent copper are used as casting alloys and become comparatively brittle as the copper content increases. The mechanical properties of both the wrought and casting alloys are subject to marked improvement by suitable heat treatments. The commercial alloy most commonly used in the heat treated condition contains about four per cent copper because this composition will produce the best combination of high tensile strength, high yield strength and high ductility.

Silicon: Silicon stands second to copper as the commonest alloying element of aluminum. The most important of the wrought silicon alloys generally do not contain more than two or three per cent silicon. However, the chief use of silicon is in casting alloys which contain from five to thirteen per cent silicon. The casting and foundry characteristics of these alloys are particularly good and for this reason these alloys find wide usage in intricate castings. Silicon alloys are not as amenable to heat treatment as are copper alloys. Even with optimum heat treatment the yield strengths and ductility of the aluminum-silicon alloys are lower than are those of aluminum-copper alloys of the same tensile strength.

Manganese: Manganese is generally used only in wrought alloys, the most important of which contains approximately one per cent manganese. These alloys do not respond well to heat treatment and for this reason they are generally strengthened by strain hardening and used in a cold rolled condition of hard temper.

Magnesium: The aluminum-magnesium alloys which are used in the wrought form contain one to five per cent magnesium. The casting alloys may contain as high as thirty per cent magnesium. These alloys are lighter than aluminum, cast well, and are rolled without difficulty if the magnesium is kept below three per cent. Both the wrought and casting alloys respond well to heat treatment, resulting in combinations which have high strength and high ductility.

Zinc: Zinc is used in amounts as high as fifteen per cent for wrought alloys, and thirty per cent for cast alloys. While high strength can readily be obtained in wrought and cast alloys this advantage is more than offset by disadvantages such as poor ductility, high specific gravity, poor casting quality, susceptibility of the wrought material to intercrystalline cracking, poor resistance to corrosion, and structural instability. The beneficial effects of heat treatment are not permanent and aluminum-zinc alloys lose the additional strength obtained by heat treatment in a few months time. Zinc is therefore rarely used as a single alloying element in aluminum and its use is generally restricted to alloys containing from five to ten per cent zinc and from two to three per cent copper.

## Heat Treatment of Aluminum Alloys

The heat treatment of aluminum alloys is simply a means of distributing the alloying elements so that they are effective in increasing the strength of the alloys. Heat treatment is effective only for those aluminum alloys which contain alloying elements whose solid solubility in aluminum is distinctly higher at elevated temperatures. Copper is the most amenable to solution treatment and for this reason it is the most widely used of the alloying elements.

The first step in the heat treatment procedure is called "solution heat treatment", which consists of heating the alloys to a temperature sufficiently high to effect essentially complete solution of the alloying elements. This temperature (850°-950° F.) is usually taken as the highest possible one which will not cause incipient fusion. Quenching from this solution temperature does not allow time for the precipitation of the alloying elements, which have lower solubility at lower temperature, and results in a supersaturated solid solution at room temperature.

TABLE III

TYPICAL MECHANICAL PROPERTIES OF WROUGHT ALUMINUM ALLOYS

| Alloy and Temper | Yield Strength 0.2% | T.S. psi. | % EL(2") 1/2" Round | Hardness BHN-500 Kg. |
|---|---|---|---|---|
| 2S-0 | 5,000 | 13,000 | 45 | 23 |
| 2S-1/4H | 13,000 | 15,000 | 25 | 28 |
| 2S-1/2H | 14,000 | 17,000 | 20 | 32 |
| 2S-3/4H | 17,000 | 20,000 | 17 | 38 |
| 2S-H | 21,000 | 24,000 | 15 | 44 |
| 24S-0 | 10,000 | 26,000 | 22 | 42 |
| 24S-T | 46,000 | 68,000 | 22 | 105 |
| 24S-RT | 57,000 | 73,000 | 18 | 116 |
| 53S-0 | 7,000 | 16,000 | 35 | 26 |
| 53S-W | 20,000 | 33,000 | 30 | 65 |
| 53S-T | 33,000 | 39,000 | 20 | 80 |
| 75S-0 | 15,000 | 34,000 | 13 | -- |
| 75S-W | 20,000 | 46,000 | 20 | -- |
| 75S-T | 65,000 | 75,000 | 10 | 150 |
| R301-0* | 10,000 | 25,000 | 22 | -- |
| R301-W | 39,000 | 59,000 | 20 | -- |
| R301-T | 41,000 | 61,000 | 9 | -- |

* Note: Reynolds Company does not use letter S on this wrought alloy.

If such a solution-treated alloy were allowed to stand at ordinary temperatures the alloying constituents would tend to precipitate from solution, in accordance with room temperature equilibrium relations. This phenomenon is commonly referred to as "aging". For some alloys this change goes on too slowly at room temperature and artificial aging at temperatures in the neighborhood of 300° F. is required; this procedure is referred to as "precipitation heat treatment". The process of aging results in increased tensile strength, yield strength, and hardness, but decreases the ductility. The specific precipitation treatment (combination of temperature and time) governs the value and the combinations of these properties. Carrying the aging treatment past the optimum time results in loss of strength and increase in ductility. This effect is known as "overaging".

The effects of solution and precipitation treatments may be removed from aluminum alloys by heating in the range of 640-670° F. This treatment, known as "annealing", is also used to remove the hardening effects of cold working and forming.

Alloy and Temper Designation

The aluminum industry uses a well defined code system by which the alloy is identified as to analysis, heat treatment and temper (degree of cold working). The wrought alloys are differentiated from the casting alloys by the letter "S" after the code number which designates the analysis - for example 24S (wrought alloy) and 47 (casting alloy). The condition of soft temper resulting from an annealing operation is designated by the addition of the letter "O" - for example 24S-O. For certain classes of alloys strain hardening is the only means of increasing the hardness. For such alloys the hard temper is designated as "H" and represents the hardness resulting from the maximum possible amount of cold work. Tempers representing intermediate degrees of cold working are represented by the fractional system: 1/4H, 1/2H, and 3/4H. Alloys which are hardened by heat treatment are designated by the letters "T" or "W". The symbol "W" is used to designate the room temperature aged condition of alloys which may also be age hardened at elevated temperatures. The symbol "T" generally designates the condition of maximum hardness obtained solely by heat treatment regardless of the temperature used for aging. If, in conjunction with age hardening, a further increase in strength is obtained by strain hardening the designation "RT" is used - for example 24S-RT.

## II. TECHNICAL ASPECTS OF ALUMINUM MANUFACTURE

### Reduction and Remelting

The production of aluminum pig involves two processes: chemical purification of the ore, and electrolytic reduction of the purified ore. The chemical purity of the resultant aluminum pig is dependent primarily on two factors; (1) the chemical purity of the refined bauxite (which runs approx. 99.8% $Al_2O_3$ with the oxides of iron, silicon and titanium as associated impurities) and (2) the operating conditions of the electrolytic cells, where, under poor operating conditions, the aluminum may be further contaminated with iron. Under present operating conditions the purity of the aluminum pig varies from 99.60 to 99.90 percent aluminum. The median quality ranges from 99.70 to 99.75 percent aluminum. It is important to note that, unlike steel, the aluminum pig cannot be purified further during the remelting and alloying operations, therefore the principal control of the purity of the final product is dependent on the quality of the original pig. Present operating conditions require that most, if not all, of the higher purity pig be used for the special corrosion resistant alloys (cladding alloys).

Remelting is essentially an operation where aluminum pig and scrap are melted down, alloyed to desired compositions, and cast into suitable size ingots for rolling. This process differs from conventional steel practice in that it is a semicontinuous operation; the furnaces run for a period of one week during which time raw materials are continually added and a portion of the molten material is periodically tapped off. At the Reynolds plant the remelting furnaces have only one hearth. Casting is accomplished by tapping off the lower quarter of the molten metal bath every eight hours. At Alcoa the charged material is melted and alloyed on one hearth, then siphoned into a holding hearth, from whence it is cast. This operation increases production since the holding hearth is tapped every two hours. It is not believed that this difference in practice makes any substantial difference in the quality of the resultant aluminum alloy. The percentage of scrap used in the furnace burden varies with the type of alloy and availability of the scrap. Both manufacturers are forced by economic considerations to use a very high percentage of scrap. Reynolds uses approximately 85% scrap, while Alcoa uses approximately 65%. The use of such high percentages of scrap is not considered good practice for production of armor plate because:

(1) Impurities and contamination from the scrap charge cannot be removed during the remelting operation, and

(2) The use of these large amounts of scrap results in uncontrolled fluctuation in the chemical analysis of the alloys.

As stated previously no impurities can be eliminated during the remelting operation, but aluminum oxide and occluded gases may be removed by the use of chlorine gas. The Reynolds Company uses the practice of bubbling chlorine gas through the molten metal. Alcoa accomplishes this by introducing aluminum chloride into the molten metal bath. No known variation in quality results from this difference in technique.

The operation of one remelting furnace for the period of one week is known as a "casting period", and all metal produced during this period is identified by a number similar to a steel heat number. The aluminum is tapped from the furnace directly into a multiple head which feeds from two to six ingots simultaneously. The ingots are not cast into a convential type mold, but rather into a shallow mold of the dimensions of the cross section of the ingot. As the metal solidifies in this shallow mold, the bottom of the mold is gradually lowered at a controlled rate until the desired length of ingot, about 100", is obtained. Such an operation is referred to as a "drop". All ingots cast at one time are identified by the week's cast number plus a sample number which applies only to those particular ingots. One chemistry sample representing all the ingots in a drop is taken when a drop is approximately one-third completed. The analysis of this sample is not reported back to the furnace operator for eight hours, and therefore, furnace adjustments necessarily lag eight hours behind sampling.

The current Army-Navy specifications have a relatively wide range of chemical tolerances on the alloying elements in structural aluminum. For example, the copper content of 24ST may vary between 3.8% and 5.0% and all the material within this range is considered to be "uniform 24ST". At the present time, when the manufacturers are forced to use a high percentage of scrap in the charge, these chemical tolerances are frequently missed.

It has been found that certain remelting furnaces show a distinct tendency to produce aluminum alloys having abnormally high or low properties. These differences cannot be attributed to variations in the chemical analysis, and apparently the reason for this behavior is not known. Similarly, the Naval Research Laboratory has found differences in the ballistic performance of the same aluminum alloy produced by different plants. In view of these facts it appears highly desirable to maintain the identity of all plates of armor as far back as the individual remelting furnaces and their charges. At the present time this practice is not followed and the identity of the ingots is lost after the original chemical check.

After casting, all ingots of high strength alloys must be homogenized (held at a temperature of approximately 960°F) to eliminate alloy segregation. If the homogenization is not complete, rolled plate material will have pronounced directional properties, and in particular, will have poor ductility in the direction normal to the surface of the plate. When tested ballistically, this type of material has shown a pronounced tendency for severe back spalling.

The homogenized ingots may be reheated for rolling, or in some cases are rolled directly from the homogenizing furnace. Rolling temperature is maintained at approximately 850° F. The initial reductions are kept small because of the fragile condition of the cast ingot. The ingots are cross rolled to the desired width, after which the ingots are turned and the remainder of the reductions to specified gauge are carried out in this same direction. Because of this practice, all aluminum plate generally will have marked directional properties.

## Heat Treatment

Important factors to be considered in the heat treatment of aluminum alloys are solution temperature, solution time, effectiveness of quench, and degree of control exercised during the aging cycle. The furnaces and equipment now in use at Reynolds and Alcoa are especially designed for the heat treatment of aluminum and appear to be adequate for the production of aluminum alloy armor. It is questionable if adequate heat treatment of aluminum plate could be successfully carried out in furnaces not specifically designed for the heat treatment of aluminum. In aluminum, development of optimum properties becomes more difficult as thickness of cross-section increases.

## III. METALLURGICAL INVESTIGATION OF ALCOA ALLOYS 61S-T 24S-T, 24S-T80, 14S-T, 75S-T.

### Introduction

As the result of a meeting held in April 1945, at N.P.G., between the representatives of Bureau of Ordnance, Naval Proving Ground and Aluminum Company of America, it was decided to make an exploratory survey of the ballistic properties of various aluminum alloys. The alloys to be tested were selected because they represented a wide range of properties of commercial alloys. These alloys are not new developments for ballistic use but are merely thick plates of structural sheet alloys having the characteristic properties of high strength and low ductility. Alcoa agreed to furnish three 4' x 4' plates of each alloy in 3/4", 1-1/4" and 1-1/2" gauges. The alloys chosen were: 61S-T, 24S-T, 24S-T80, 14S-T, and 75S-T. The general characteristics of these alloys are summarized in the following paragraphs.

### Alloy 61S

The alloy 61S has a nominal analysis of 1.0% Mg, .6% Si, .25% Cr. It is available commercially in the "O" (annealed) "W" (naturally aged) and "T" (artificially aged) conditions in the form of plates, bars and tubing. The mechanical properties and hardness of this alloy in the "O", "W", and "T" conditions are:

| Condition | Yield (.2%) Strength | Tensile Strength | %EL | BHN (500 Kg) |
|---|---|---|---|---|
| 61S-O | 8,000 psi. | 18,000 psi. | 22 | 30 |
| 61S-W | 21,000 psi. | 35,000 psi. | 22 | 65 |
| 61S-T | 39,000 psi. | 45,000 psi. | 12 | 95 |

This alloy is generally used in applications requiring good formability and good corrosion resistance; because of its low strength it is not used in highly stressed structures.

### Alloy 24S

The alloy 24S has a nominal analysis of 4.5% Cu, 1.5% Mg, 0.6% Mn. It is available commercially in the form of plates, bars, tubing, and forgings. Originally it was available commercially in the "O" (annealed), "T" (room temperature aged condition) and "RT" ("T" alloy which had been cold rolled) conditions.

Its use has been so widespread that numerous special treatments have been developed to enhance its mechanical properties. The following table presents the conditions of 24S which are officially recognized.

| Condition | Treatment |
|---|---|
| 24S-0 | Annealed |
| 24S-T (reheat treat) | Reheat treated material, aged at room temperature, and having 0% cold work. |
| 24S-T | Room temperature aged material with 1% cold work. |
| 24S-T (stretched channels) | Room temperature aged material with 4% cold work. |
| 24S-RT | Room temperature aged material with 6% cold work |
| 24S-T80 | Reheat treat material, aged at 250° - 400° F., having 0% cold work. |
| 24S-T81 | Material aged 250°-400° F., having 1% cold work. |
| 24S-T84 | Material aged 250°-400° F., having 4% cold work. |
| 24S-T86 | Material aged 250°-400° F., having 6% cold work. |

The mechanical properties and hardness of 24S in a number of representative conditions are as follows:

| Condition | Yield (.2%) Strength | Tensile Strength | %EL 2" | BHN (500 Kg) |
|---|---|---|---|---|
| 24S-0 | 10,000 psi. | 26,000 psi. | 22 | 42 |
| 24S-T | 45,000 psi. | 68,000 psi. | 22 | 105 |
| 24S-RT | 55,000 psi. | 70,000 psi. | 13 | 116 |
| 24S-T80 | 56,000 psi. | 72,000 psi. | 22 | - |
| 24S-T81 | 66,000 psi. | 73,000 psi. | 17 | - |
| 24S-T84 | 70,000 psi. | 73,000 psi. | 15 | - |
| 24S-T86 | 72,000 psi. | 74,000 psi. | 12 | - |

This alloy is generally used structurally; its corrosion properties can be improved by cladding the surface with pure aluminum (Alclad) or a corrosion resistant alloy.

Alloy 14S

The alloy 14S has a nominal composition of 4.4% Cu, 8% Mn, .8% Si, .4% Mg. It is available commercially in the form of plates, forgings, and extrusions and is heat treated to "O" (annealed), "W" (room temperature aged), and "T" (artificially aged condition). The mechanical properties and hardness of 14S in these representative conditions are as follows:

| Condition | Yield (.2%) Strength | Tensile Strength | %EL 2" | BHN (500 Kg) |
|---|---|---|---|---|
| 14S-0 | 10,000 psi. | 25,000 psi. | 22 | 50 |
| 14S-W | 39,000 psi. | 59,000 psi. | 18 | 110 |
| 14S-T | 59,000 psi. | 66,000 psi. | 9 | 145 |

This alloy is generally used for high strength plates and forgings; its corrosion properties can be improved by cladding with pure aluminum (Alclad) or a corrosion resistant alloy.

Alloy 75S

The alloy 75S has a nominal composition of 1.5% Cu, 2.5% Mg, 6.0% Zn, .25% Cr. It is available commercially in the "O" (annealed), "W" (naturally aged) and "T" (artificially aged) conditions in the form of plates, bars, and forgings.

The mechanical properties and hardness of this alloy in the "O", "W", and "T" conditions are:

| Condition | Yield (.2%) Strength | Tensile Strength | %EL 2" | BHN (500 Kg) |
|---|---|---|---|---|
| 75S-O | 15,000 | 32,000 | 16 | 60 |
| 75S-W | 20,000 | 46,000 | 20 | 80 |
| 75S-T | 66,000 | 76,000 | 10 | 160 |

At the present this alloy is only used structurally. Its poor corrosion properties are improved by cladding with a high strength zinc alloy (1.25% Zn, .10% Mn).

## Test Program

When plates of the alloys which have been described were received an identification system was adopted by which individual sections of individual plates, and the location of metallurgical samples taken from these plates, could be easily identified. Metallurgical test specimens were taken from opposite corners of each of these plates (a and c corners) as shown in Figure 1.

## Chemical Analysis

Since Alcoa reported that all plates of each alloy designation were cast from one heat of metal, a chemical analysis was made on only one plate of each alloy composition; this plate was chosen as the 3/4" plate of each alloy. The results of these analyses are as follows:

| | Cu | Si | Mn | Mg | Zn | Cr | Fe |
|---|---|---|---|---|---|---|---|
| 14S-T | 4.6 | 1.00 | .80 | .48 | .11 | 0 | .15 |
| 24S-T | 4.2 | .13 | .59 | 1.57 | .03 | 0 | .16 |
| 61S-T | .25 | .42 | .03 | .99 | .02 | 0 | .12 |
| 75S-T | 1.58 | .13 | .13 | 2.56 | 5.97 | 0 | .13 |

The analyses were found to agree very well with those submitted by Alcoa, and with the nominal analyses of the subject alloys. It should be noted that the iron content has been kept low indicating good control of the remelting practice on these particular heats.

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Table IV - PART III

1-1/2" GAUGE PLATES

| | | T.S. | .2% Y.S. | %EL | %R.A. | B.H.N. |
|---|---|---|---|---|---|---|
| L 61 | a | 45,300 | 40,800 | 16.5 | 40.5 | 96 |
| L | c | 45,200 | 41,000 | 17.0 | 41.6 | 88 |
| T | a | 46,700 | 36,400 | 14.0 | 24.8 | |
| T | c | 46,100 | 44,800 | 12.0 | 23.7 | |
| L 24 | a | 71,900 | 52,500 | 15.0 | 17.0 | 137 |
| L | c | 72,000 | 51,700 | 14.0 | 17.0 | 136 |
| T | a | 69,800 | 50,000 | 13.0 | 15.9 | |
| T | c | 71,100 | 50,600 | 13.0 | 15.3 | |
| L 80 | a | 71,300 | 60,300 | 11.0 | 15.9 | 143 |
| L | c | 72,000 | 58,000 | 12.5 | 17.0 | 146 |
| T | a | 71,600 | 60,500 | 10.0 | 13.0 | |
| T | c | 71,800 | 59,300 | 10.5 | 13.4 | |
| L 14 | a | 72,000 | 67,000 | 9.0 | 14.1 | 147 |
| L | c | 75,200 | 65,500 | 11.0 | 14.8 | 147 |
| T | a | 66,600 | 63,500 | 2.5 | 3.1 | |
| T | c | 73,000 | 65,000 | 3.0 | 3.9 | |
| L 75 | a | 81,400 | 71,000 | 9.5 | 16.6 | 162 |
| L | c | 84,200 | 75,200 | 10.5 | 15.6 | 164 |
| T | a | 81,400 | 72,500 | 9.0 | 13.7 | |
| T | c | 81,700 | 73,500 | 7.5 | 11.5 | |

Specimen Designation:

61 = 61 S-T
24 = 24 S-T
80 = 24 S-T80
14 = 14 S-T
75 = 75 S-T

a & c = plate positions opposite quarters of plates
L = Long. spec.
T = Trans. spec.

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Table IV - PART II

1-1/4" GAUGE PLATES

| | | T.S. | .2% Y.S. | % EL | %R.A. | B.H.N. |
|---|---|---|---|---|---|---|
| L 61 | a | 45,500 | 41,000 | 18.0 | 38.5 | 95 |
| L | c | 46,000 | 41,875 | 18.0 | 44.6 | 98 |
| T | a | 46,200 | 41,450 | 14.5 | 23.7 | |
| T | c | 46,700 | 41,900 | 13.5 | 24.4 | |
| L 24 | a | 70,000 | 47,500 | 20.0 | 22.6 | 138 |
| L | c | 69,800 | 45,800 | 20.0 | 22.5 | 127 |
| T | a | 68,400 | 50,150 | 13.5 | 12.6 | |
| T | c | 67,200 | 43,800 | 9.5 | 15.7 | |
| L 80 | a | 72,000 | 57,000 | 14.5 | 24.3 | 146 |
| L | c | 71,900 | 55,400 | 15.5 | 23.0 | 142 |
| T | a | 68,600 | 56,100 | 8.0 | 6.6 | |
| T | c | 69,500 | 58,200 | 11.0 | 14.4 | |
| L 14 | a | 77,500 | 67,800 | 9.5 | 14.8 | 150 |
| L | c | 74,200 | 64,700 | 12.0 | 6.6 | 144 |
| T | a | 69,000 | 66,750 | 2.5 | 1.4 | |
| T | c | 69,700 | 60,200 | 3.5 | 7.4 | |
| L 75 | a | 87,500 | 78,000 | 9.5 | 18.1 | 166 |
| L | c | 79,300 | 68,300 | 6.5 | 13.5 | 162 |
| T | a | 81,600 | 72,350 | 7.5 | 9.3 | |
| T | c | 83,700 | 75,000 | 7.0 | 10.4 | |

Specimen Designation:

61 = 61 S-T
24 = 24 S-T
80 = 24 S-T80
14 = 14 S-T
75 = 75 S-T

a & c = plate positions opposite quarters of plates.

L = Long. spec.
T = Trans. spec.

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TABLE IV - PART I

SUMMARY OF TENSILE RESULTS
ALCOA ALUMINUM ALLOY EXPERIMENTAL ARMOR PLATE

3/4" GAUGE PLATES

| | | T.S. | .2 % Y.S. | % El | % R.A. | B.H.N. |
|---|---|---|---|---|---|---|
| L 61 | a | 44,500 | 39,500 | 18.5 | 44.3 | 93 |
| L | c | 44,700 | 41,000 | 17.5 | 44.6 | 96 |
| T | a | 45,100 | 39,000 | 15.0 | 33.8 | |
| T | c | 46,000 | 40,000 | 14.0 | 31.8 | |
| L 24 | a | 69,500 | 52,000 | 19.5 | 27.2 | 133 |
| L | c | 68,200 | 51,200 | 19.0 | 25.9 | 131 |
| T | a | 69,400 | 44,400 | 17.0 | 20.2 | |
| T | c | 68,600 | 47,500 | 16.0 | 17.5 | |
| L 80 | a | 69,300 | 55,300 | 15.5 | 27.2 | 142 |
| L | c | 69,300 | 55,500 | 15.5 | 26.9 | 140 |
| T | a | 71,200 | 55,700 | 13.0 | 15.6 | |
| T | c | 70,700 | 57,200 | 12.0 | 17.0 | |
| L 14 | a | 73,300 | 65,500 | 10.5 | 16.3 | 146 |
| L | c | 74,300 | 67,000 | 10.5 | 18.1 | 150 |
| T | a | 72,200 | 64,000 | 5.0 | 7.3 | |
| T | c | 75,500 | 68,000 | 9.5 | 15.2 | |
| L 75 | a | 85,600 | 78,600 | 9.0 | 15.6 | 169 |
| L | c | 83,000 | 73,500 | 9.0 | 14.8 | 160 |
| T | a | 85,700 | ------- | 7.5 | 13.0 | |
| T | c | 80,300 | 70,000 | 10.0 | 15.9 | |

Specimen Designation:

61 = 61 S-T
24 = 24 S-T
80 = 24 S-T80
14 = 14 S-T
75 = 75 S-T

a & c = plate positions opposite quarters of plates
L = Long. spec.
T = Trans. spec.

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Tensile Properties

Tensile specimens were taken in longitudinal and transverse directions as shown in Figure 1. Table IV summarizes all test data obtained as the result of this survey. Figures 2, 3, 4, 5, and 6 present these data in graphical form for each alloy as a function of the plate gauge. These data were found to agree with similar, less detailed, data submitted by Alcoa. It appeared however that the 24S-T80 plates could more properly be classified as 24S-T81; this conclusion was later substantiated by a metallographic examination. While it is known that the tensile strength and yield strength of thick plates of aluminum alloys will generally be lower than that of sheet material, the data of table IV show no consistent variation of these properties with plate gauge. It is expected that such a relation would be found if sufficient tests would be available to permit a statistical study. The reduction of area and percent elongation, as expected, show a fairly consistent drop with increase in plate gauge. Figure 7 shows the appearance of the fractures of representative tensile specimens.

Brinell Hardness

The Brinell hardness of each plate was determined on a bar cut immediately adjacent to the tensile bar of the specific section under study. Two bars were taken from each plate as shown in Figure 1, one to represent the "a" section and the other the " c " section. The hardness measurements were made on a carefully prepared surface on a plane perpendicular to the plate surface, using a 10mm. ball under a load of 3000 kg. applied for 15 seconds. The hardness measurements on alloy 61S-T were made using a 500 kg. load since the relative softness of this plate caused the 3000 kg. load to give excessively large indentations.

Table IV summarizes the test data obtained as the result of this survey. The reproducibility of these determinations appears to be approximately within ±4 B.H.N. It was found that similar hardness measurements made on the unprepared plate surface of the unclad plates (plate 14S-T was the only plate which had been clad.) gave identical hardness values with approximately the same degree of reproducibility.

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TABLE V
SUMMARY OF TENSILE IMPACT TESTS
ALCOA ALUMINUM ALLOY EXPERIMENTAL ARMOR PLATE

| Alloy | Test Direction | 3/4" Gauge Plates A Sec. | 3/4" Gauge Plates C Sec. | 3/4" Gauge Plates Ave. | 1-1/4" Gauge Plates A Sec. | 1-1/4" Gauge Plates C Sec. | 1-1/4" Gauge Plates Ave. | 1-1/2" Gauge Plates A Sec. | 1-1/2" Gauge Plates C Sec. | 1-1/2" Gauge Plates Ave. |
|---|---|---|---|---|---|---|---|---|---|---|
| 61S-T | Normal | | | | 10 9 7 | 7 7 8 | 8 | 10 11 | 10 10 | 10 |
| | Long | 45 45 | 57 47 | 48 | 41 40 | 40 47 | 42 | 56 48 | 45 50 | 50 |
| | Trans. | 42 40 | 42 40 | 41 | 42 38 | 37 37 | 39 | 50 53 | 43 37 | 43 |
| 24S-T | Normal | | | | 7 6 7 | 5 8 6 | 7 | 5 7 | 7 10 | 7 |
| | Long | 84 96 | 107 95 | 95 | 73 73 | 84 95 | 81 | 92 95 | 95 79 | 90 |
| | Trans. | 79 70 | 71 82 | 75 | 62 60 | 55 56 | 58 | 62, 75, 88 | 73, 95, 95 | 81 |
| 24S-T80 | Normal | | | | 4 7 3 | 4 4 4 | 4 | 5 5 | 7 8 | 6 |
| | Long | 63 70 | 58 92 | 71 | 53 52 | 47 40 | 48 | 55 52 | 74 72 | 63 |
| | Trans. | 50 58 | 56 57 | 58 | 67 64 | 50 51 | 53 | 45, 50, 46 | 52 52 | 50 |
| 14S-T | Normal | | | | 4 5 7 | 6 3 3 | 5 | 5 4 | 8 5 | 6 |
| | Long | 43 46 | 47 46 | 46 | 43 43 | 31 36 | 38 | 56 45 | 48 47 | 49 |
| | Trans. | 35 45 | 38 44 | 41 | 45 45 | 21 24 | 35 | 21, 21, 24 | 28, 34, 24 | 25 |
| 75S-T | Normal | | | | 3 4 3 | 3 4 3 | 3 | 4 5 | 3 3 | 4 |
| | Long | 45 49 | 58 53 | 51 | 50 48 | 42 44 | 46 | 44 54 | 63 65 | 57 |
| | Trans. | 33 45 | 51 43 | 43 | 51 47 | 39 35 | 43 | 47, 49, 44 | 45, 43, 41 | 45 |

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The Brinell hardness of metals is a function of the yield strength and the tensile strength. In the case of the aluminum alloys tested, the relationship between these variables has been determined by empirical means and is presented in Figure 8 in the form of a double-entry chart. The accuracy of this empirical relation is illustrated by the comparison of the actual hardness values with those predicted by the tensile test results. Using the experimental results obtained on this program, the probable difference (probable error) between the predicted and the observed hardness values was found to be less than 2 points Brinell for all plates except those of 24S-T80 alloy. The actual hardness of the 24S-T80 plates is consistently higher than that predicted by the tensile test results by about 5 points Brinell. This discrepancy may be associated with a difference in the rate of work hardening of this alloy with respect to the other alloys since the metallographic examination indicates that some cold work has already been performed on 24S-T80 plates.

Tensile Impact Tests

Tensile impact specimens were taken in the longitudinal and transverse directions in the "a" and "c" sections of the plates as shown in Figure 1. In addition, normal specimens were taken in these same locations on the 1-1/4"and 1-1/2" plates. The design of these specimens is also shown in Figure 1. Table V summarizes all test data obtained as the result of this survey, and Figures 10 and 11 present these data graphically. It is noted that there is a marked difference in the amount of energy absorbed in the fracturing of specimens of different alloys. For example, in the longitudinal direction 24S-T required approximately twice as much energy to fracture as 14S-T. As expected the toughness is highest in the longitudinal direction and least in the normal direction. It is surprising however to note that this difference is approximately ten fold. Such low toughness in the normal direction indicates the presence of planes of weakness in the rolling plane. This conclusion was confirmed metallographically.

In addition to the differences which may be attributed to the alloy content and to the orientation of the sample, the graphical presentation of these data on Figures 10 and 11 indicates that there is a systematic variation of this property with the plate thickness. As expected, the 3/4" plates show superior properties. The reason for the consistently inferior properties of the 1-1/4" plates with respect to the 1-1/2" plates is presently being investigated, more data of the manufacturing methods are needed for this investigation. Figures 12 and 13 show the appearance of the fractures on the tensile impact specimens.

Twist Test

Twist testing had been used by N. P. G. to detect the presence of laminations in homogeneous steel armor. This test consists of twisting a longitudinal specimen to a point where the specimen either fails in pure shear or opens up to show the presence of laminations. The application of this test to aluminum alloy armor has yielded promising results. The type of specimen used is sketched in Figure 1. Figure 9 shows the result of the application of this test to the 1-1/4" plates of the subject alloys. The plates (14S-T, 75S-T, 24S-T80) which cracked and spalled badly in the ballistic test are easily identified by the brittle laminated appearance of the twist test fracture. The plates which performed satisfactorily (24S-T, 61S-T) show a ductile shear failure. In its present form the results of this test are purely qualitative. It is planned to obtain quantitative results by conducting these tests in a torsion impact machine.

Macroscopic Study

Sections were cut in the longitudinal and transverse directions of the 1-1/4" plates for macroscopic study. These sections were carefully prepared on the face perpendicular to the plate surface and acid etched for usual examination. The appearance of the acid etched sections (see Figure 14) show that all plates are sound and uniform. The 14S-T plate is the only one which shows a clad surface. What appears to be cladding on the 24S-T plate is in reality a thin recrystallized surface layer.

Microscopic Study

The microstructure of these alloys is presented and discussed in Part II of this report, issued under separate cover.

## IV. BALLISTIC TESTS OF ALCOA ALLOYS

### Description of Testing Procedures

As previously described, each plate tested on this phase of the program was divided into four sections, the opposite quarters of each plate, "a" and "c", were used for penetration tests with armor piercing projectiles while the remaining quarters, "b" and "d", were given shock tests with high explosive projectiles. Duplicate tests were conducted on each of the pairs of plate quarters; a comparison of the test results indicates the accuracy of the ballistic tests and the uniformity of the individual plates. The average gauge of each section of each plate was determined by constructing a contour map indicating the thickness of the plate over the entire surface.

The penetration tests were conducted at normal obliquity using Caliber .30 and .50 APM2 projectiles fired from the standard aircraft type machine guns. The velocity of each impact was measured and the limit velocity was evaluated as follows:

$$V_{50} = \frac{\Sigma V + (Nu - Ns)\ 25}{Nu + Ns}$$

Where:

$V_{50}$ is the estimate of the striking velocity of which 50% of the projectiles will defeat the armor.

$\Sigma V$ is the sum of the velocities of all impacts between the velocity of the lowest successful impact and the highest unsuccessful impact.

Nu is the number of unsuccessful impacts (no penetration of an .02 Dural fragment screen placed 6" behind armor).

Ns is the number of successful impacts (penetration of fragment screen).

The 3/4" and 1-1/4" plates were shock tested at 20° obliquity with 20mm HE projectiles fitted with Mk. 26-0 fuzes; the 1-1/2" plates were tested under similar conditions with 1.1 HE Mk. 1 projectiles fitted with Mk. 34 fuzes.

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TABLE VII

SUMMARY OF BALLISTIC SHOCK TEST RESULTS

3/4" Plates: 20mm HE - Mk. 26-0 Fuze - 20° Obliquity
1-1/4", 1-1/2" Plates: 1.1 HE - Mk. 34 Fuze - 20° Obliquity

| Plate Number | | Gauge Inches | Limit Velocity | |
|---|---|---|---|---|
| 61 | B | .779 | 1798 | |
| | D | .777 | 1830 | |
| 24 | B | .748 | 1986 | |
| | D | .744 | 1970 | |
| 80 | B | .756 | 2004 | |
| | D | .759 | 1960 | |
| 14 | B | .754 | 1947 | |
| | D | .754 | 1895 | |
| 75 | B | .766 | 2017 | Cracked |
| | D | .767 | 2018 | Cracked |
| 61 | B | 1.280 | 2319 | |
| | D | 1.282 | 2240 | |
| 24 | B | 1.270 | 2243 | |
| | D | 1.275 | 2414 | |
| 80 | B | 1.275 | 2330 | |
| | D | 1.279 | 2260 | |
| 14 | B | 1.266 | Shattered | |
| | D | 1.258 | Shattered | |
| 75 | B | 1.259 | Shattered | |
| | D | 1.264 | Shattered | |
| 61 | B | 1.498 | 2449 | |
| | D | 1.497 | 2389 | |
| 24 | B | 1.527 | 2501 | |
| | D | 1.529 | 2543 | |
| 80 | B | 1.537 | 2410 | |
| | D | 1.537 | 2463 | Cracked |
| 14 | B | 1.528 | 2379 | Cracked |
| | D | 1.533 | 2394 | |
| 75 | B | 1.511 | ---- | |
| | D | 1.513 | Shattered | |

Specimen Designation:

61 = 61 S-T 14 = 14 S-T
21 = 24 S-T 75 = 75 S-T
80 = 24 S-T80

B & D = plate positions opposite quarters of plates.

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TABLE VI - PART II

SUMMARY OF BALLISTIC PENETRATION TEST RESULTS

Caliber .50 APM2 - 0° Obliquity

| Plate Number | Gauge Inches | Brinell Hardness | Actual Limit Velocity in f.s. | Limit Velocity Predicted by Figure 15 |
|---|---|---|---|---|
| 61 A | .782 | 93 | 1289 | 1288 |
| C | .775 | 96 | 1302 | 1302 |
| 24 A | .743 | 133 | 1423 | 1418 |
| C | .749 | 131 | 1425 | 1420 |
| 80 A | .757 | 142 | 1451 | 1447 |
| C | .758 | 140 | 1448 | 1446 |
| 14 A | .753 | 146 | 1402 | 1441 |
| C | .753 | 150 | 1420 | 1447 |
| 75 A | .767 | 169 | 1430 | 1444 |
| C | .766 | 160 | 1444 | 1458 |
| 61 A | 1.285 | 95 | 1680 | 1692 |
| C | 1.279 | 98 | 1687 | 1706 |
| 24 A | 1.272 | 138 | 1902 | 1888 |
| C | 1.272 | 127 | 1880 | 1869 |
| 80 A | 1.274 | 146 | 1898 | 1915 |
| C | 1.281 | 142 | 1909 | 1909 |
| 14 A | 1.256 | 150 | 1887 | 1912 |
| C | 1.267 | 144 | 1868 | 1903 |
| 75 A | 1.265 | 166 | 1968 | 1952 |
| C | 1.259 | 162 | 1931 | 1940 |
| 61 A | 1.495 | 96 | 1824 | 1848 |
| C | 1.501 | 88 | 1812 | 1797 |
| 24 A | 1.526 | 137 | 2057 | 2082 |
| C | 1.530 | 136 | 2080 | 2083 |
| 80 A | 1.540 | 143 | 2107 | 2118 |
| C | 1.535 | 146 | 2112 | 2126 |
| 14 A | 1.527 | 147 | 2074 | 2122 |
| C | 1.532 | 147 | 2074 | 2126 |
| 75 A | 1.509 | 162 | 2170 | 2159 |
| C | 1.516 | 164 | 2186 | 2170 |

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TABLE VI - PART I

SUMMARY OF BALLISTIC PENETRATION TEST RESULTS

Caliber .30 APM2 - 0° Obliquity

| Plate Number | Gauge Inches | Brinell Hardness | Actual Limit Velocity in f.s. | Limit Velocity Predicted by Figure 15 |
|---|---|---|---|---|
| 61 A | .782 | 93 | 1651 | 1623 |
| C | .775 | 96 | 1607 | 1632 |
| 24 A | .743 | 133 | 1799 | 1764 |
| C | .749 | 131 | 1819 | 1766 |
| 80 A | .757 | 142 | 1839 | 1811 |
| C | .758 | 140 | 1841 | 1807 |
| 14 A | .753 | 146 | 1808 | 1818 |
| C | .753 | 150 | 1805 | 1829 |
| 75 A | .767 | 169 | 1937 | 1894 |
| C | .766 | 160 | 1940 | 1873 |
| 61 A | 1.285 | 95 | 2183 | 2167 |
| C | 1.279 | 98 | 2181 | 2187 |
| 24 A | 1.272 | 138 | 2407 | 2441 |
| C | 1.272 | 127 | 2398 | 2380 |
| 80 A | 1.274 | 146 | 2450 | 2486 |
| C | 1.281 | 142 | 2463 | 2473 |
| 14 A | 1.256 | 150 | 2414 | 2483 |
| C | 1.267 | 144 | 2423 | 2468 |
| 75 A | 1.265 | 166 | 2557 | 2565 |
| C | 1.259 | 162 | 2543 | 2541 |
| 61 A | 1.495 | 96 | 2349 | 2372 |
| C | 1.501 | 88 | 2382 | 2300 |
| 24 A | 1.526 | 137 | 2713 | 2726 |
| C | 1.530 | 136 | 2711 | 2723 |
| 80 A | 1.540 | 143 | 2706 | 2783 |
| C | 1.535 | 146 | 2780 | 2799 |
| 14 A | 1.527 | 147 | 2717 | 2795 |
| C | 1.532 | 147 | 2735 | 2801 |
| 75 A | 1.509 | 162 | 2871 | 2862 |
| C | 1.516 | 164 | 2883 | 2882 |

Specimen Designation:
61 = 61 S-T    14 = 14 S-T
24 = 24 S-T    75 = 75 S-T
80 = 24 S-T80

A & C = plate positions opposite quarters of plates.

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The characteristics of the armor piercing projectiles used in these tests are summarized in the following Table:

| Projectile Cal. Type | Number Measured | Average Diameter | Weight Without Jacket or Windshield | $M/D^3$ in lbs/cu.ft. |
|---|---|---|---|---|
| .30 APM2 | 20 | 0".24444 | .012039 lbs. | 1425 |
| .50 APM2 | 20 | 0".42717 | .055996 lbs. | 1241 |
| 20mm APM95 | 5 | 0".76855 | .25291 lbs. | 962 |

## Test Results

The ballistic results obtained on these aluminum alloy plates are summarized in Tables VI, VII, and VIII.

## V. DISCUSSION OF BALLISTIC TEST RESULTS

Correlation of Mechanical and Ballistic Tests.

It has been established that the penetration resistance of homogeneous steel armor depends primarily upon the hardness factor and secondarily upon the toughness or ductility of the material. Since the mechanisms of penetration in the case of aluminum armor have been found to be essentially similar to those of steel armor, these test results have been analyzed to determine the relationship between the following factors, which have been found to control the penetration resistance of steel.

1. Limit Energy Function "U" = $M/d^3\ V_{50}{}^2$

   In this equation, M and d are the mass and diameter of the armor piercing projectiles and $V_{50}$ is the optimum estimate of the velocity at which 50% of the projectiles will penetrate the armor.

2. Equivalant e/d Ratio "$e_1/d$"

   This is the usual armor penetration function - namely, the ratio of plate thickness to projectile diameter - modified to account for the lighter density of the aluminum alloys. $e_1/d = e/2.8d$.

3. Brinell Hardness Number "BHN"

   The Brinell hardness measurements were made in the standard manner using a 3000 kg. load on all plates except those of alloy 61S-T, in which case a 500 kg. load was employed.

When the values of limit energy function, "U", for all plates except those of the 14S-T alloy are plotted as a function of $e_1/d$ value and the Brinell hardness, the individual test results fit a smooth, curved surface with the small average deviation of only 0.8 of 1%. This relationship is shown graphically in Figure 15. It will be noted that the limit energy required to penetrate the plate completely is virtually linear with the plate thickness having a slight upward curvature at the higher values of $e_1/d$. This behavior is in accordance with theoretical studies of armor penetration. Except in the region of the lowest $e_1/d$ values, the penetration resistance of aluminum alloys is found to increase steadily with hardness.

This phenomenon of optimum hardness is similar to, but not as pronounced as that observed in the case of steel. In other words, if aluminum could be made harder than the current alloy, 75S-T, and still retain sufficient ductility, the penetration resistance would be expected to improve. Consequently, if the values of M, e, d, and BHN are known, the limit velocity of any aluminum plate may be predicted with a fair degree of accuracy by a process of two-way interpolation using the data presented in Figure 15. This "Standard Performance Chart" is particularly useful since it permits a comparison of any new alloys to be tested with the present alloys even though the new plates do not have exactly the same thickness and hardness.

Thus it is apparent that the hardness of aluminum alloy plates gives an accurate index of the penetration resistance of the plate to A. P. bullets in the $^{e}1/^{d}$ ranges studied. It should be noted that the alloy composition need not be known for a valid evaluation by means of this simple, mechanical test. Since the Brinell hardness is related to the tensile strength as shown in Figure 8, a correlation between these ballistic results and the tensile strengths is to be expected. However, the Brinell hardness test is generally employed for experimental and acceptance testing of light armor, since it is a rapid, non-destructive test which permits an extensive survey of each plate.

Shock Resistance

The ability of an aluminum alloy to withstand a severe shock, such as given in the high explosive projectile test, depends on its toughness, or more simply on its combination of ductility and strength.

The mechanical test best suited for the evaluation of the toughness of aluminum alloys was found to be the tensile impact test. The details of this test have been discussed in a previous section on tensile impact tests and the data obtained from a survey of the subject plates has been plotted in Figure 10. It should be noted that the alloys having high longitudinal and transverse tensile impact toughness also had the ability to resist cracking on the ballistic shock test. Conversely, the plates which show low tensile impact toughness could not stand up under this test and generally failed by cracking. Alloy 61S-T appears to be an exception, in that it had low tensile impact toughness and yet showed good resistance to shock.

However, alloy 61S-T is considerably softer and its ballistic penetration resistance is very much lower than the other aluminum alloys. In its present form the use of the tensile impact test should be restricted to comparison of shock properties of aluminum alloy plates having approximately similar hardness, or approximately equal penetration resistance. The correlation obtained on this basis is excellent.

Resistance to Spalling

The resistance to spalling on a penetration test depends on the toughness of the plate in the thickness (normal) direction. Discontinuities affecting the homogeneity of the metal always have a markedly deleterious effect on the normal ductility of armor plate and invariably result in spalling. The tensile impact test was applied to the study of this normal toughness of the subject aluminum alloy plates and the data obtained from the survey have been reported in a previous section and plotted in Figure 11. The low ductility in the thickness direction, indicates that severe discontinuities existed in all plates; the softer plates were comparatively less affected by these discontinuities while conversely the harder plates were affected the most. It should be noted that the plates which have the highest impact toughness in the thickness direction gave smaller spalls than plates with low impact toughness.

Effect of Rolling Reduction

The results of these tests indicated a systematic variation of the ballistic performance of the aluminum alloys with the gauge of the plates - the thicker plates developed less resistance to penetration per unit of thickness. These plates were rolled from ingots of the same size and therefore the 1-1/2" plates have had less reduction during rolling than the 3/4" plates. Evidence of this gauge effect has been demonstrated in the following manner:

The three plate thicknesses and the two projectile calibers afforded a total of six values of $e_1/d$. The smooth surface of Figure 15 fits all experimental points except those corresponding to the 3/4" plates tested with Cal. .30 projectiles, which are consistently about 2% high. This superiority of the 3/4" plates was checked by additional tests in which the 1-1/2" plates were tested with 20mm AP Projectiles.

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TABLE VIII

COMPARISON OF BALLISTIC RESULTS OBTAINED ON ROLLED AND MACHINED PLATES OF ALLOY 24ST80

Rolled Plate: 3/4" Thickness
Machined Plate: 1-1/2" Plate Machined down to 3/4" Gauge

| ROLLED PLATE: | Cal. 30 APM2 | | Cal. 50 APM2 | | 20mm HE | |
|---|---|---|---|---|---|---|
| Plate Number | 80 A | 80 C | 80 A | 80 C | 80 B | 80 D |
| Gauge - Inches | 0".757 | 0".758 | 0".757 | 0".758 | 0".756 | 0".759 |
| $e_1/d$ Value | 1.106 | 1.107 | 0.633 | 0.633 | | |
| Brinell Hardness | 142 | 140 | 142 | 140 | | |
| Actual Limit | 1839 | 1841 | 1451 | 1448 | 2004 | 1960 |
| Theoretical Limit* | 1811 | 1807 | 1447 | 1446 | 1922+ | 1928+ |
| % of Std. Performance | 101.6 | 101.9 | 100.2 | 100.1 | 104.5 | 101.7 |
| Average | 101.7% | | 100.2% | | 103.0% | |

| MACHINED PLATE: | Cal. 30 APM2 | Cal. 50 APM2 | 20mm HE |
|---|---|---|---|
| Gauge - Inches | 0".880 | 0".860 | 0".900 |
| $e_1/d$ Value | 1.284 | 0.307 | |
| Brinell Hardness | 143 | 143 | |
| Actual Limit | 2008 | 1528 | 2050 |
| Theoretical Limit* | 1973 | 1548 | 2172+ |
| % of Std. Performance | 101.8% | 98.7% | 94.4% |

* Computed from Figure 15
\+ From NPG Report 18-43 - 10 August 1943.

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It was thus possible to compare the 3/4" and the 1-1/2" plates at approximately the same value of $e_1/d$. The 1-1/2" plates, were found to be approximately 8% less efficient in resisting penetration than the 3/4" plates on an energy-per-unit weight basis. In order to establish definitely that these results were not projectile effects, but actually were caused by differences in the quality of the 3/4" and 1-1/2" plates, one additional test was conducted in which a 1-1/2" plate of 24S-T80 was machined down to 3/4" thickness. This reduced thickness plate was tested under exactly the same conditions as the regular 3/4", 24S-T80 plate. A comparison of the results obtained on these plates is given in Table VIII where it is seen that the machined 3/4" plate was markedly inferior to the rolled 3/4" plates except in the case of the Caliber .30 test. These results may be interpreted as follows: The thinner plates have had a greater reduction during rolling which has resulted in a more complete break-down of the cast structure. This improvement in the structure in turn has been reflected in the ballistic performance of the material, the most pronounced effect being observed on those ballistic tests which require the greatest degree of shock resistance.

Effect of Cladding

As stated in a previous section, all plates except those of the 14S-T alloy were unclad. When evaluated on a basis of the total plate thickness, the penetration resistance of the 14S-T alloy plates was found to be consistently inferior (2-3%) to that predicted by the "Standard Performance" curves. This relatively poor showing of the 14S-T plates may be attributed to the thick cladding of very soft aluminum on each surface of the plates. This cladding was ".06 thick on the 1-1/4" plates and thus amounted to almost 10% of the total plate thickness. Since the performance of aluminum armor is dependent upon the hardness, it is clear that this soft cladding material cannot contribute a proportionate share of the ballistic resistance and any evaluation based on the total plate thickness will indicate the clad plates to be inferior. This explanation of the performance of the 14S-T plates was checked by testing one additional 3/4" 14S-T plate from which the cladding had been removed by machining. In this case, the .30 caliber resistance increased to an above average value whereas the Caliber .50 A. P. resistance remained about 98% of standard performance. The continued poor performance of the bare 14S-T plate against Caliber .50 gunfire may be associated with the loss of petals on the back side of the plate.

The petals were retained to a large extent on the clad 14S-T plates by the ductile cladding material and thus the gain in resistance due to the removal of soft cladding appears to be compensated by the loss in resistance due to the poor petalling condition. The loss of petals on the Caliber .30 impacts on this plate was not as pronounced as in the case of the Caliber .50 impacts.

| Projectile Cal.Type | Gauge Inches | Brinell Hardness | Limit of Unclad 14S-T Plate | Limit Estimated from Fig. 15 | % of Standard Performance |
|---|---|---|---|---|---|
| 30 APM2 | .590 | 146 | 1632 fs | 1595 fs | 102.3% |
| 50 APM2 | .600 | 146 | 1250 | 1279 | 97.7% |

VI. CONCLUSIONS

The results of the experimental program may be summarized as follows:

1. The resistance of aluminum alloy plates to penetration by armor piercing projectiles has been correlated with the Brinell hardness of the material.

2. The shock resistance of aluminum alloy plates has been correlated with the tensile impact properties of the material. For plates at approximately the same hardness level, this test will distinguish between plates that will fail or pass the ballistic test.

3. It has been determined that a definite relationship exists between the Brinell hardness, the yield strength and the tensile strength of aluminum alloys; if the tensile properties are known the Brinell hardness of age hardened alloys without cold work can be predicted to within ±4 B.H.N.

4. The results of these tests indicate that although cladding is instrumental in preventing the loss of petals the cladding material is of such low hardness that the overall efficiency of the armor is lowered.

5. These tests indicate that the amount of reduction during rolling affects the ballistic performance of aluminum armor; the performance of the armor decreasing as the degree of reduction is lowered.

EXPERIMENTAL ALUMINUM ALLOY ARMOR PLATE

METHOD OF SECTIONING PLATES - LOCATION OF MECHANICAL

TEST SPECIMENS - DESIGN OF SPECIMENS

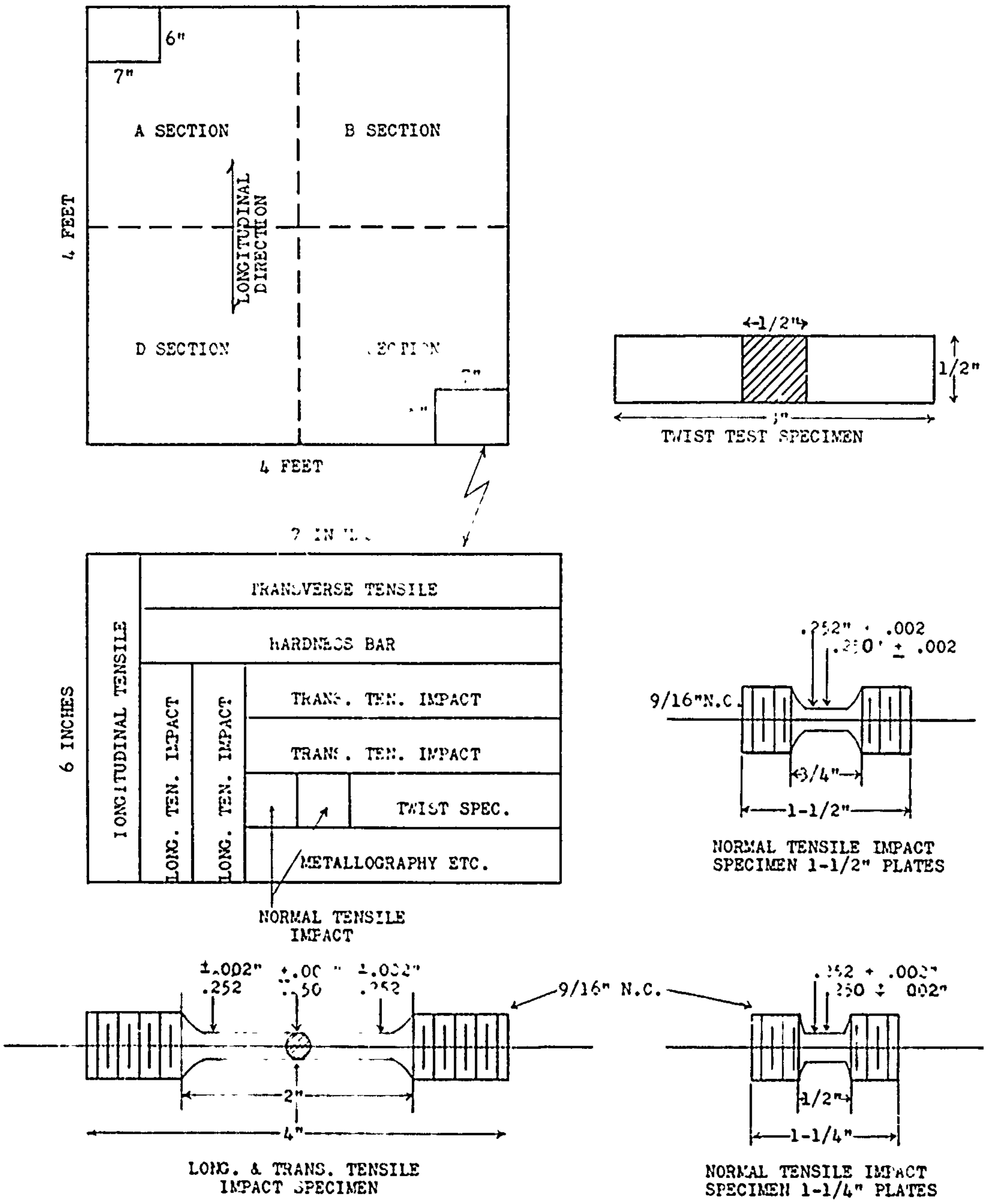


FIGURE 1

[redacted]

NPG PHOTO NO.2869 (APL)

THE TENSILE PROPERTIES OF ALCOA 61S-T ALUMINUM ALLOY PLATES OF EXPERIMENTAL ARMOR

"A" AND "C" REPRESENT VALUES FROM OPPOSITE CORNERS OF THE PLATES

ANALYSIS: .62%Si, .22%Fe, .25%Cu, .98%Mg, .25%Cr

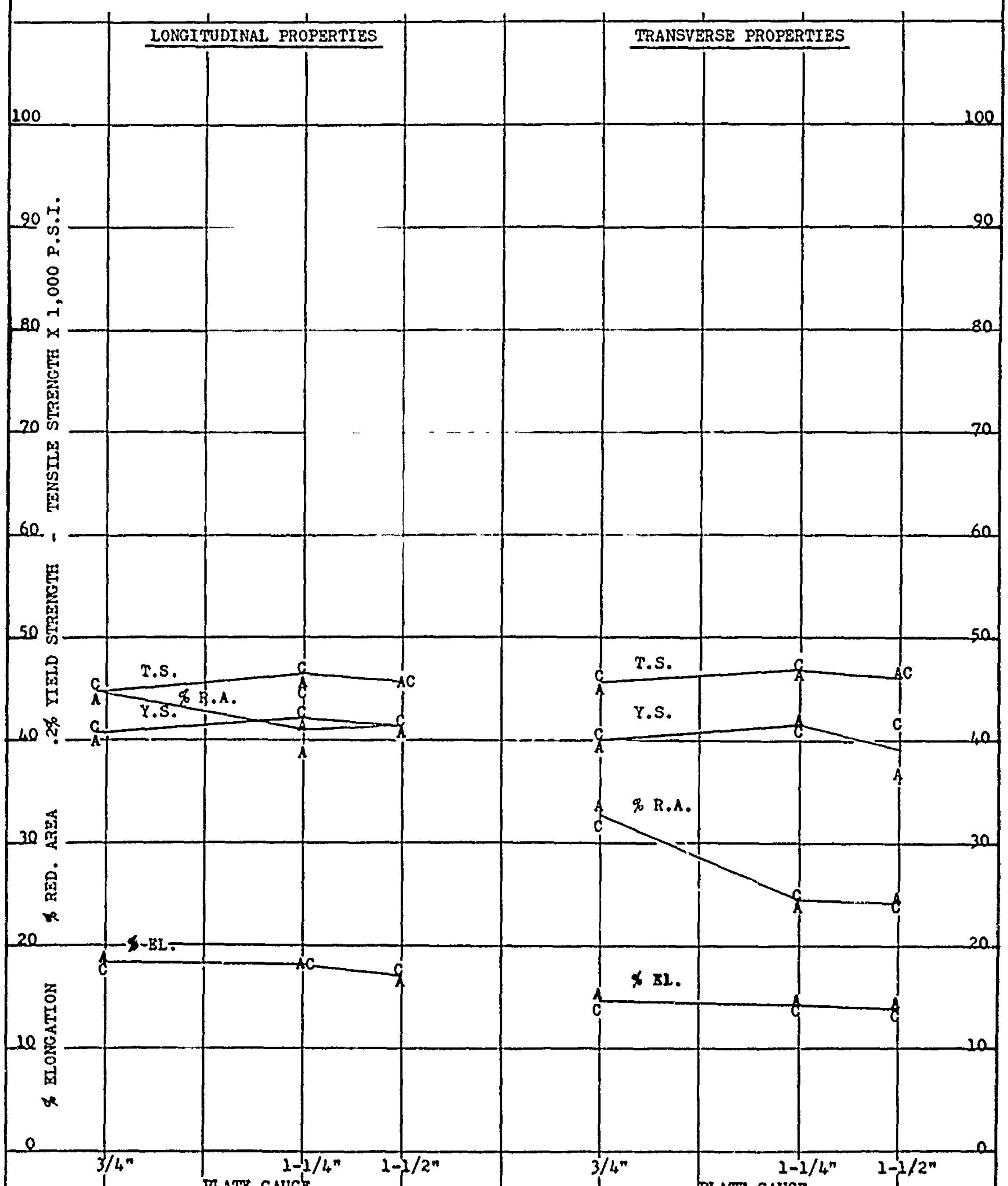


FIGURE 2

[redacted]

NPG PHOTO NO. 2848 (APL)

THE TENSILE PROPERTIES OF ALCOA 24S-T ALUMINUM ALLOY PLATES OF EXPERIMENTAL ARMOR

"A" AND "C" REPRESENT VALUES FROM OPPOSITE CORNERS OF THE PLATES

ANALYSIS; .15%Si, .22%Fe, 4.30%Cu, .57%Mn, 1.56%Mg

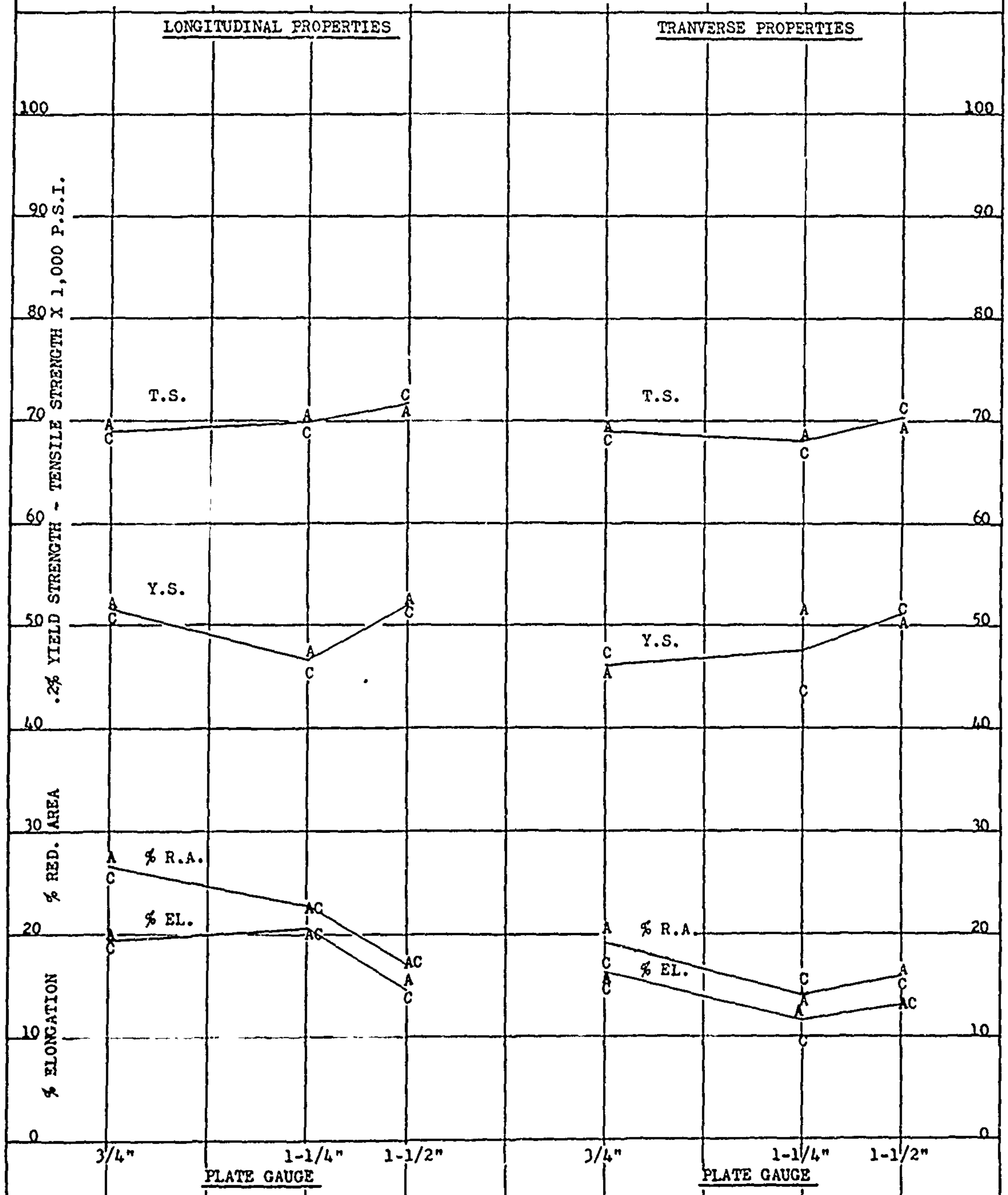


FIGURE 3

[redacted] NPG PHOTO NO. 2850 (APL)

THE TENSILE PROPERTIES OF ALCOA 24S-T80 ALUMINUM ALLOY PLATES OF EXPERIMENTAL ARMOR

"A" AND "C" REPRESENT VALUES FROM OPPOSITE CORNERS OF THE PLATES

ANALYSIS: .14%Si, .20%Fe, 4.40%Cu, .56%Mn, 1.47%Mg

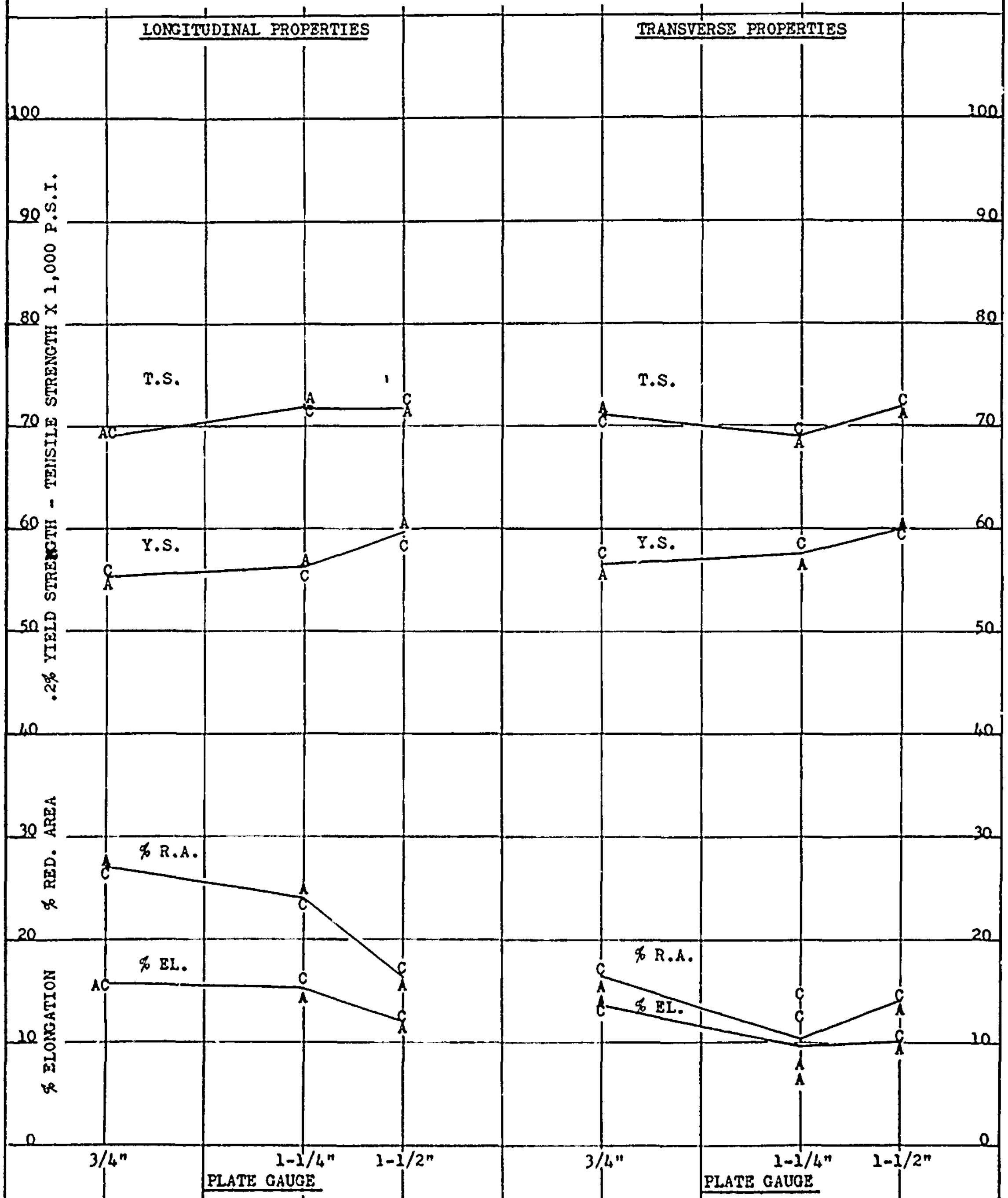


FIGURE 4

[redacted]

NPG PHOTO NO. 2851 (APL)

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THE TENSILE PROPERTIES OF ALCOA 14S-T ALUMINUM ALLOY PLATES OF EXPERIMENTAL ARMOR

"A" AND "C" REPRESENT VALUES FROM OPPOSITE CORNERS OF THE PLATES

ANALYSIS: 1.03%Si, .27%Fe, 4.62%Cu, .77%Mn, .49%Mg

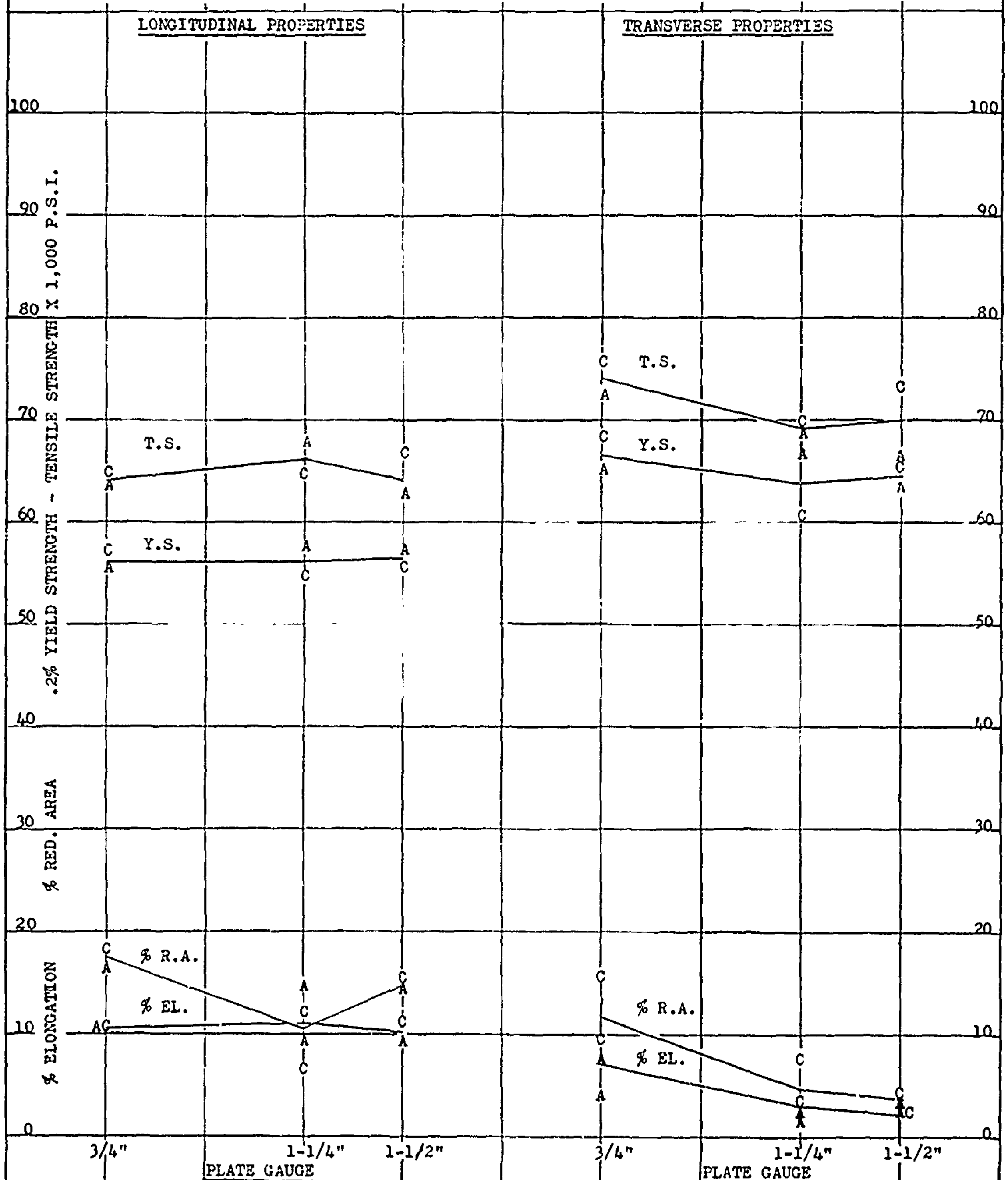



FIGURE 5

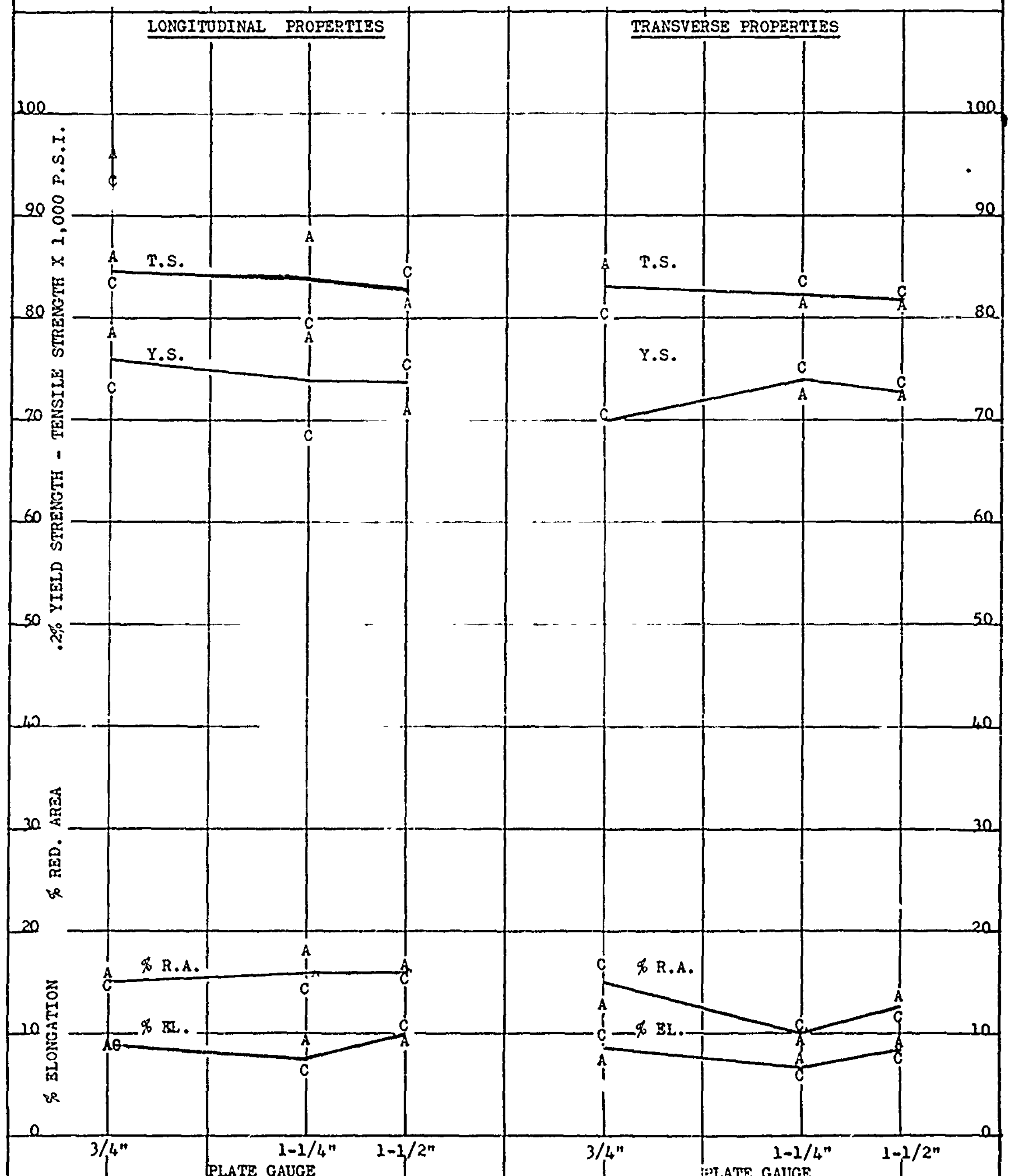
[redacted]

NPG PHOTO NO. 2852 (APL)

THE TENSILE PROPERTIES OF ALCOA 75S-T ALUMINUM ALLOY PLATES OF EXPERIMENTAL ARMOR

"A" AND "C" REPRESENT VALUES FROM OPPOSITE CORNERS OF THE PLATES

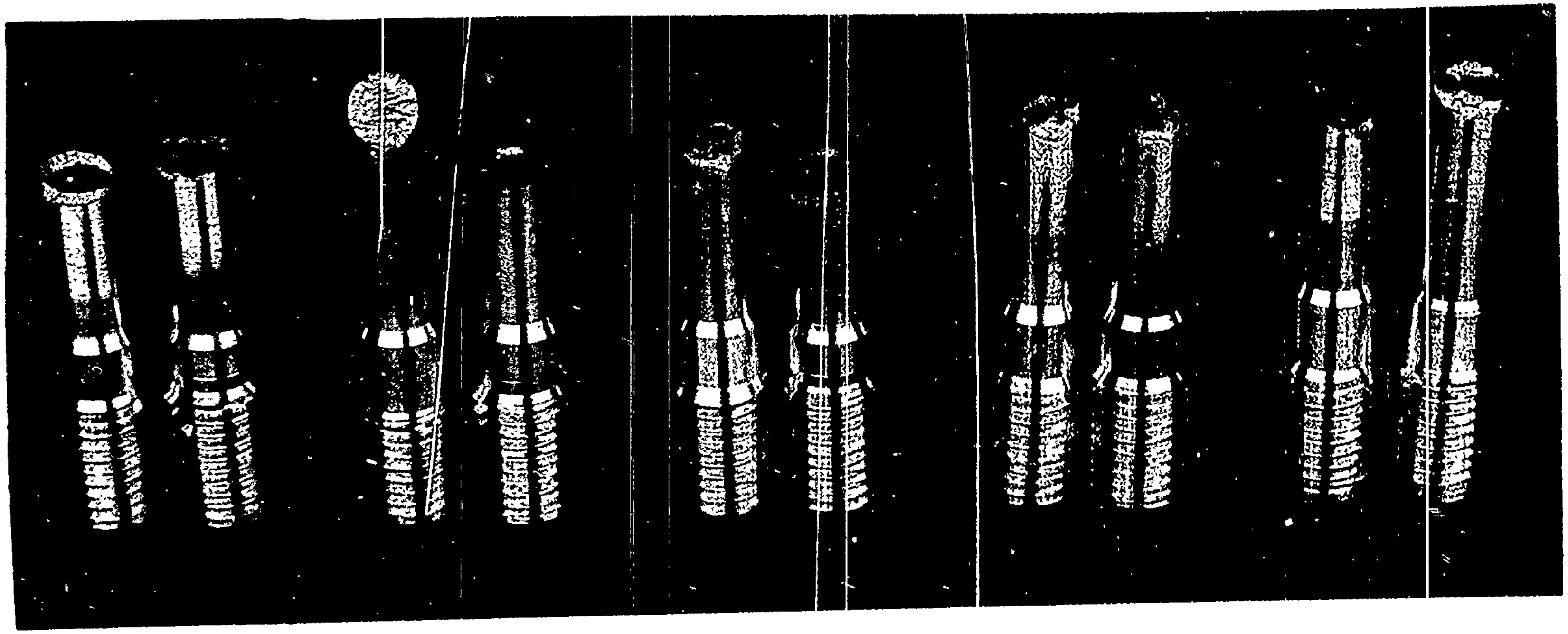
ANALYSIS: .13%Si, .21%Fe, 1.57%Cu, .15%Mn, 2.46%Mg, .27%Cr, 5.90%Zn, .04%Ti




[redacted]

FIGURE 6

NPG PHOTO NO. 2849 (APL)



| ALLOY | 14S-T | 24S-T | 24S-T80 | 61S-T | 75S-T |
|---|---|---|---|---|---|
| DIRECTION | L T | L T | L T | L T | L T |

Appearance of fractures of tensile specimens from Alcoa 1-1/4" aluminum alloy plates; .505" specimens taken in direction indicated.

[redacted] NPG. PHOTO NO. 2854 (APL)

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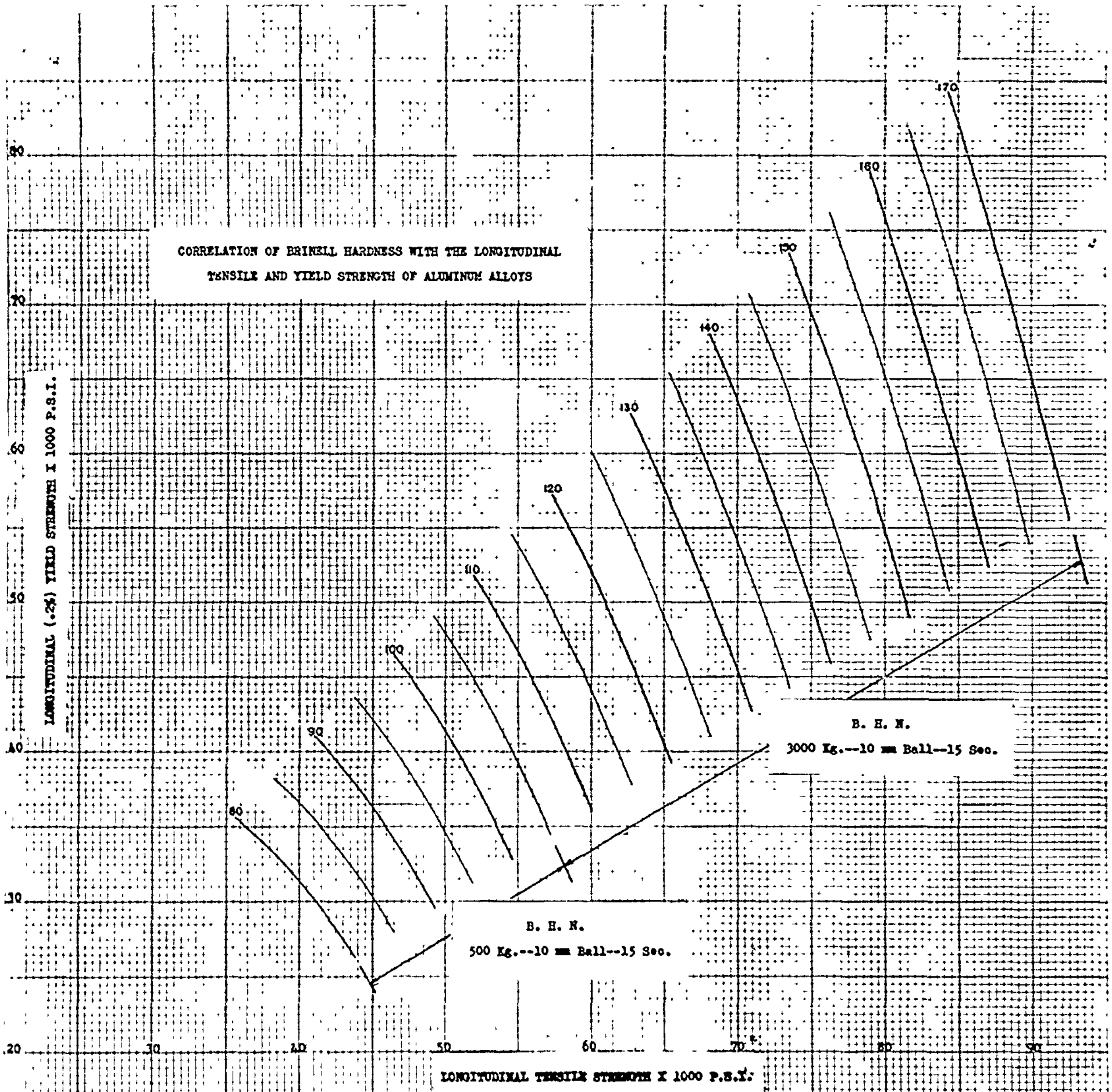
FIGURE 7




COMPARISON OF MEASURED BRINELL HARDNESS VALUES WITH VALUES PREDICTED BY THE ABOVE CHART

| PLATE | 61S-T | | 24S-T | | 24S-T80 | | 14S-T | | 75S-T | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ala | 93 | 92 | 133 | 133 | 142 | 135 | 146 | 146 | 169 | 169 |
| Alc | 96 | 94 | 134 | 131 | 140 | 135 | 150 | 148 | 160 | 163 |
| Bla | 95 | 95 | 138 | 132 | 146 | 139 | 150 | 153 | 166 | 171 |
| Blc | 98 | 96 | 127 | 130 | 142 | 138 | 144 | 147 | 162 | 156 |
| Cla | 96 | 94 | 137 | 137 | 143 | 140 | 147 | 145 | 162 | 160 |
| Clc | 88 | 94 | 136 | 137 | 146 | 140 | 147 | 148 | 164 | 165 |
| Average Error | 2.3% | | 1.2% | | 0.9%* | | 1.2% | | 1.7% | |

First figure is measured value, second figure predicted value.
* After increasing predicted value by 4%.

FIGURE 8

NPG PHOTO NO. 3000 (APL)

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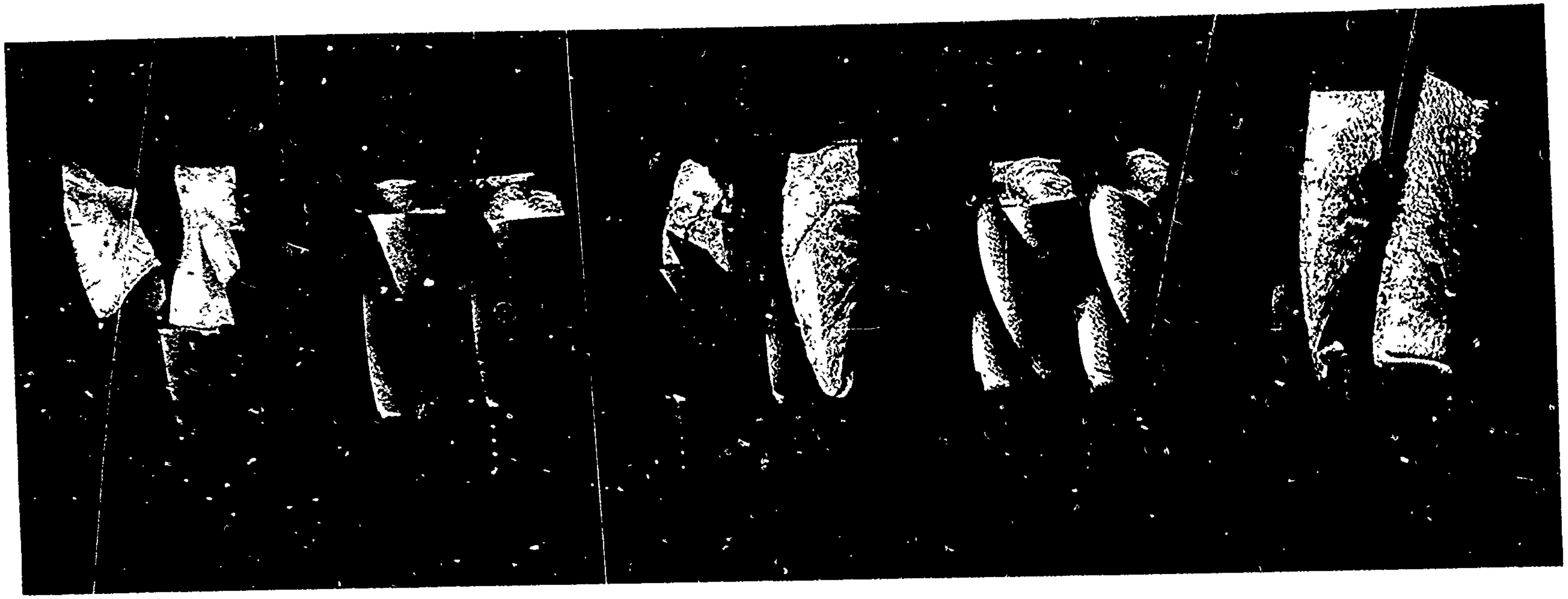


| ALLOY | 14S-T | 24S-T | 24S-T80 | 61S-T | 75S-T |
|---|---|---|---|---|---|
| ANGLE OF TWIST | 75°-80° | 85°-90° | 90°-90° | 175°-190° | 60°-70° |

Twist specimens of Alcoa aluminum alloy. Duplicate longitudinal specimens, 1/2" x 1/2" x 3", from 1-1/4" plates--gauge length of twist 1-3/4".

[redacted] NPG. PHOTO NO. 2853 (APL)

FIGURE 9

CORRELATION OF CRACKING ON H.E. SHOCK TESTS (.20M.M. & 1.1") WITH THE TENSILE IMPACT PROPERTIES OF ALCOA ALUMINUM ALLOY PLATES OF EXPERIMENTAL ARMOR. EACH VALUE REPRESENTS THE AVERAGE OF AT LEAST FOUR TESTS MADE WITH TWO TESTS AT OPPOSITE CORNERS OF THE PLATES. SPECIMENS .250" DIAM. 2" GAUGE LENGTH

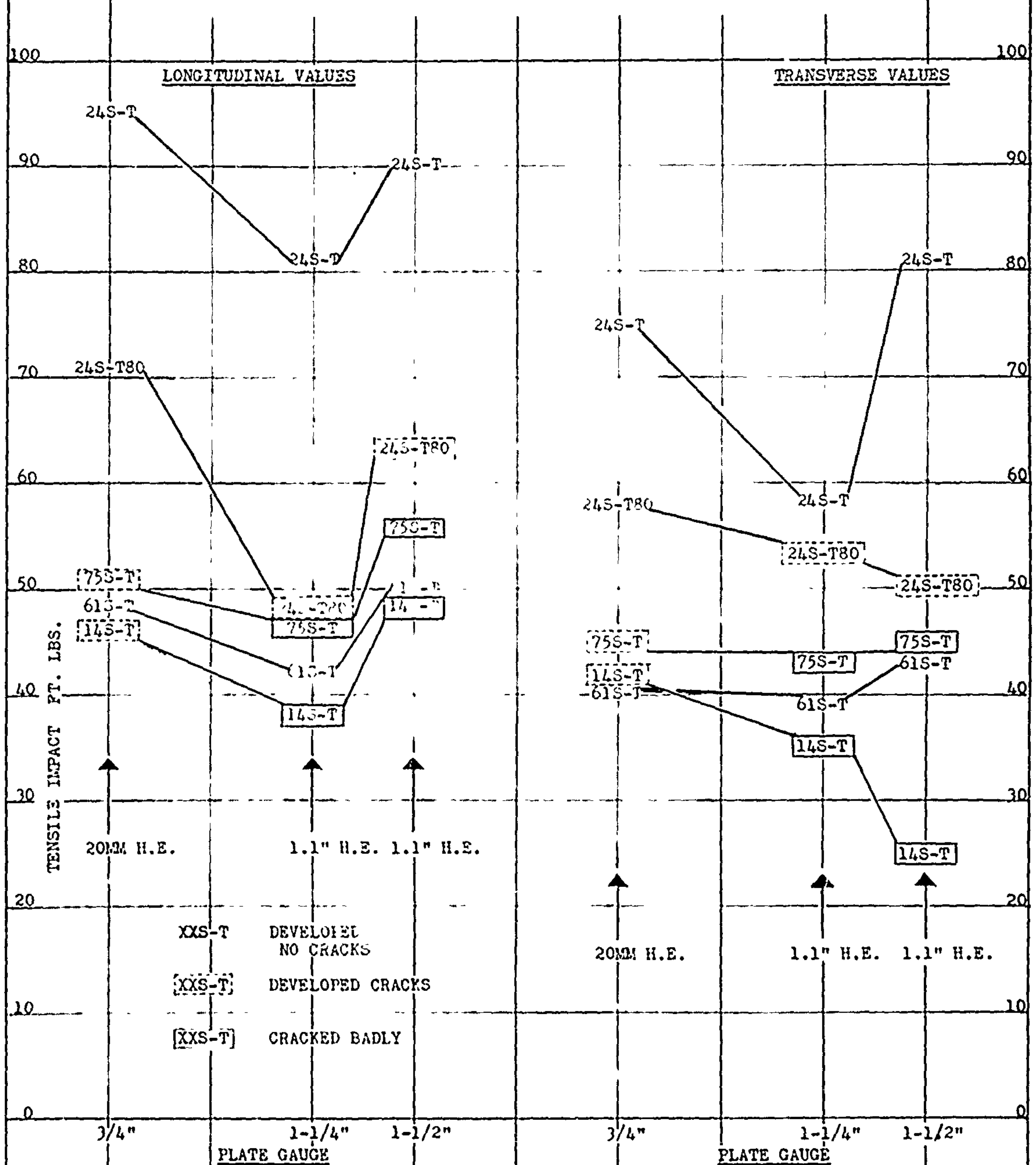



FIGURE 10

[redacted]

NPG PHOTO NO. 2857 (APL)

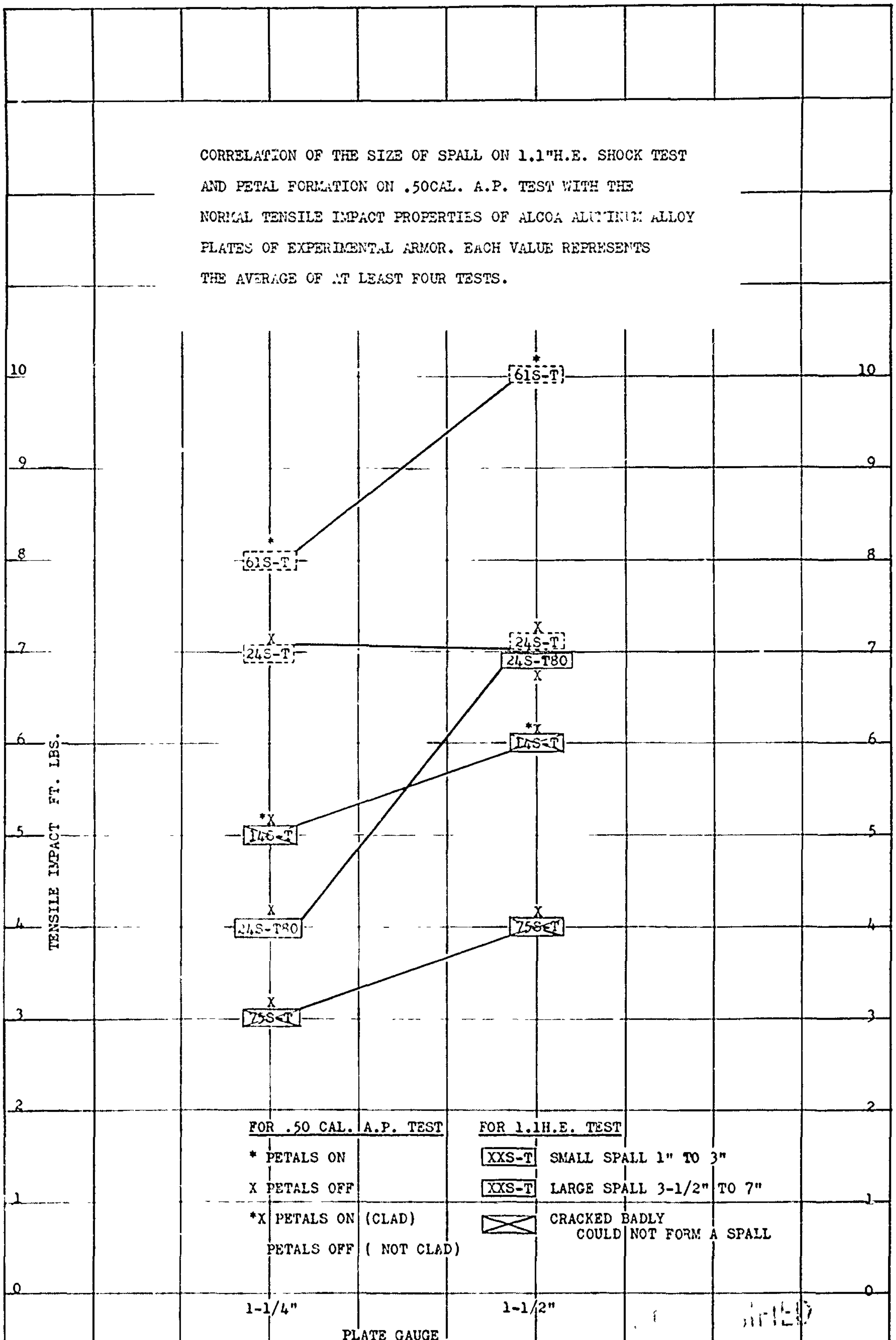
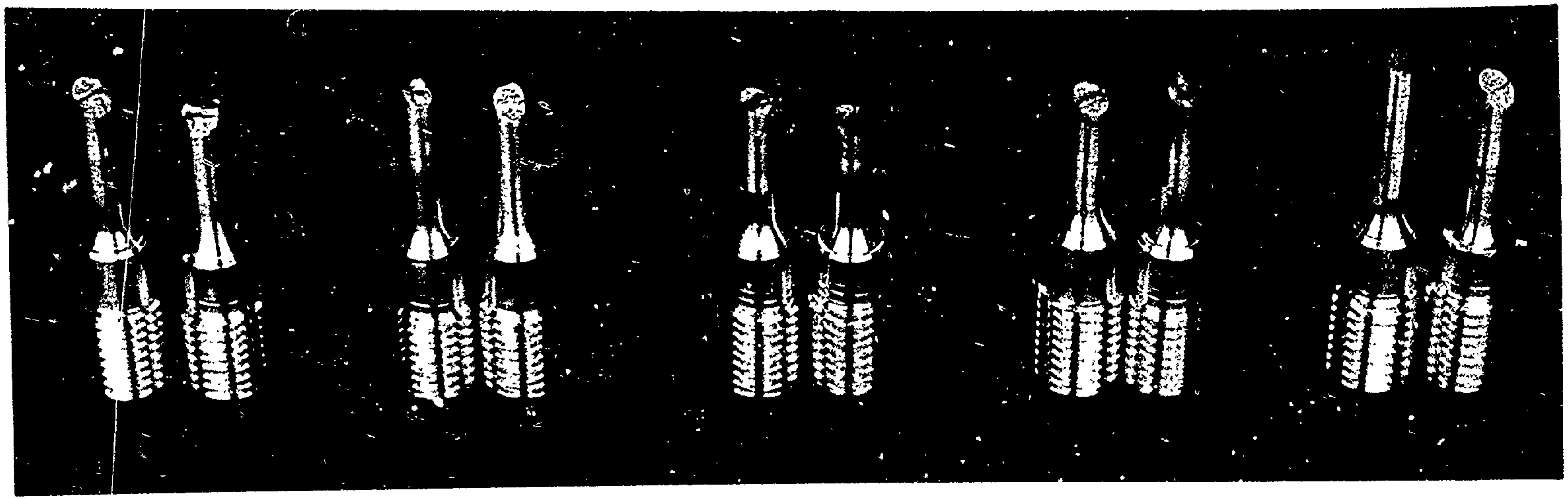



FIGURE 11

[redacted]

NPG PHOTO NO. 2858 (APL)



| ALLOY | 14S-T | 24S-T | 24S-T80 | 61S-T | 75S-T |
|---|---|---|---|---|---|
| DIRECTION | L T | L T | L T | L T | L T |

Appearance of fractures of longitudinal and transverse tensile impact specimens from Alcoa 1-1/4" aluminum alloy plates. Specimens .250" diameter, 2" gauge length.

[redacted] NPG. PHOTO NO. 2655 (APL)

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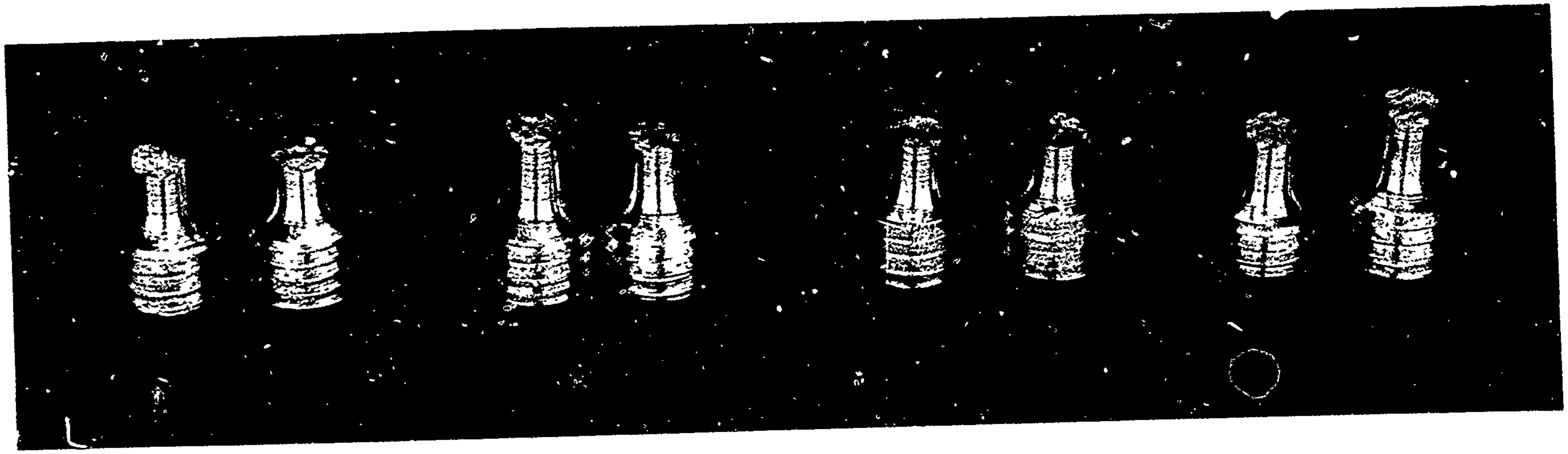
FIGURE 12



| ALLOY | 14S-T | 24S-T | 24S-T80 | 61S-T |
|---|---|---|---|---|

Appearance of fractures of normal tensile impact specimens from Alcoa 1-1/4" aluminum alloy plates. Specimens .250" diameter, 1/2" gauge length.

[redacted] NPG. PHOTO NO. 2855 (APL)

FIGURE 13

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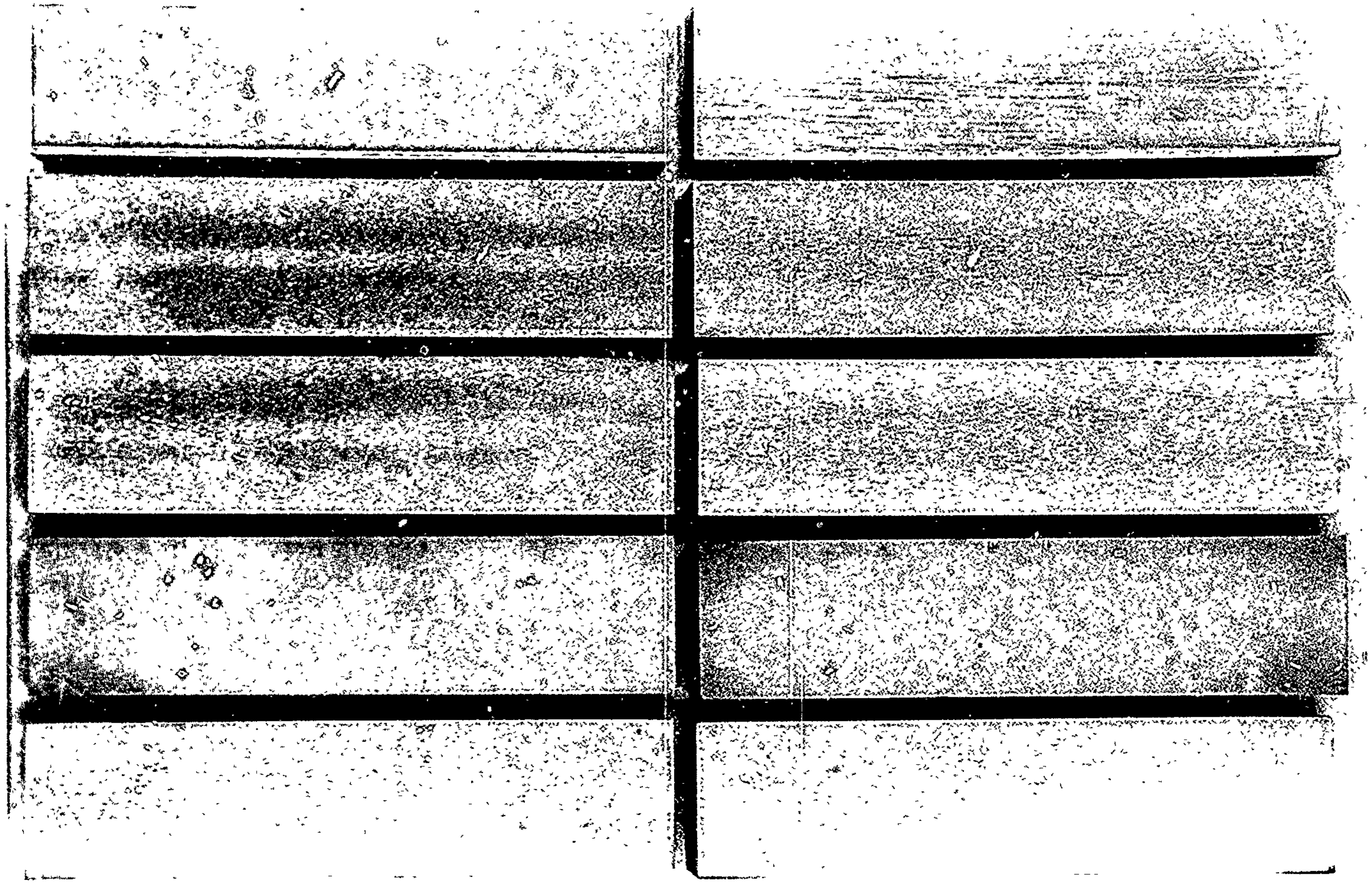
14S-T

24S-T

24S-T80

61S-T

75S-T



LONGITUDINAL TRANSVERSE

Macroetched sections of 1-1/4" plates of Alcoa aluminum alloys. Etched with $HNO_3$-HF-HCl-$H_2O$.

[redacted] NPG. PHOTO NO. 2657 (APL)

FIGURE 14

NPG PHOTO 2771(APL)
11 JULY 1945

# PENETRATION RESISTANCE OF ALUMINUM ALLOY ARMOR

## VS CALIBER .30 & .50 APM2 PROJECTILES AT NORMAL OBLIQUITY

LIMIT ENERGY FUNCTION "U" vs BRINELL HARDNESS & EQUIVALENT e/d RATIO

"U" = $\frac{M}{d^3} V_{50}^2$ where M is core weight in pounds
d is core diameter in feet
$V_{50}$ is limit velocity at which 50% of the projectiles penetrate the plate

"BHN" measured with 3000 kg. load (500 kg on 61ST)

"Equivalent e/d" = Plate thickness ÷ 2.8d

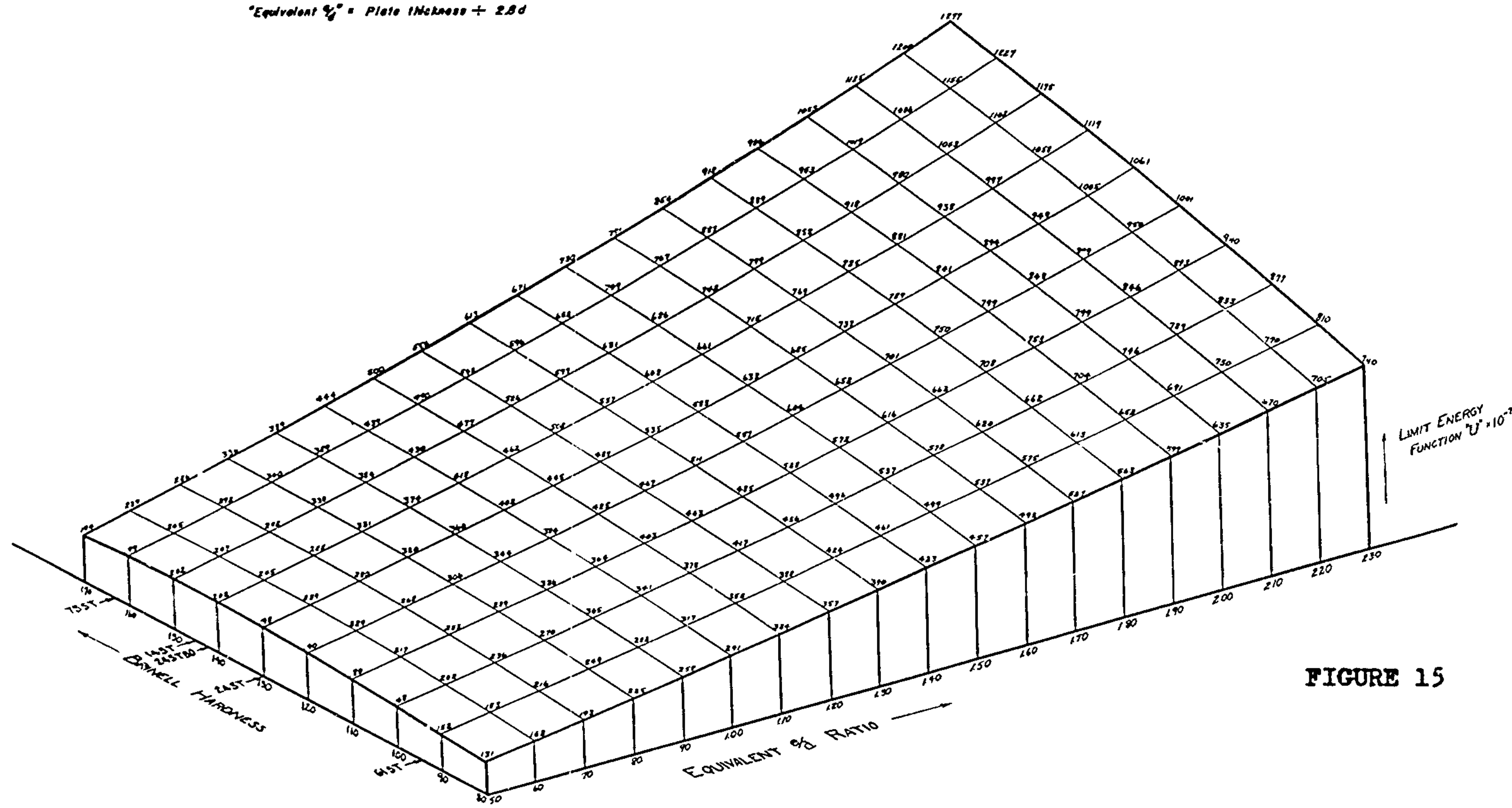



FIGURE 15

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# FIRST PARTIAL REPORT ON ALUMINUM ALLOY ARMOR

## PART II

## THE METALLOGRAPHY OF THE ALCOA ALUMINUM ALLOYS 61S-T, 24S-T, 24S-T80, 14S-T, 75S-T

INTRODUCTION

SPECIMEN PREPARATION

RESULTS OF METALLOGRAPHIC STUDY

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED.

CLASSIFICATION CANCELLED (CHANGED TO) Unclassified ... NavOrd ltr a652/1178; PAH 55" 10/31/73
ON 8/31/76 (DATE) B. Broyles (SIGNATURE) (RANK)

NOTE: The section dealing with the metallurgy and ballistics has been issued under separate cover, as PART I of this report.

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UNCLASSIFIED

INTRODUCTION

The first section of this report dealt with the ballistic and mechanical properties of a series of aluminum alloy plates which had been submitted by Alcoa for ballistic testing. This section of the report, Part II, deals with the metallographic study of the subject alloy plates.

This study has been made as comprehensive as possible in order to obtain a basic understanding of the alloys comprising the first controlled group of aluminum armor plate submitted for experimental ballistic testing by the U. S. Navy.

A specimen was taken from each gauge (3/4". 1-1/4", 1-1/2") of each alloy (61S-T, 24S-T, 24S-T80, 14S-T, 75S-T) and sectioned so as to permit examination of the center and surface positions on planes parallel to and perpendicular to the surface of the plate. This detailed investigation was deemed necessary because of the almost complete lack of information on the metallography of thick plates of aluminum alloys. If plates, thicker than the present ones, are to be considered for future experimental development it will be necessary to have such knowledge of the characteristics of heavy aluminum alloy sections.

SPECIMEN PREPARATION

The procedure for the preparation of metallographic specimens of aluminum alloys does not differ greatly from that ordinarily employed for the preparation of other alloys, except that greater care must be exercised due to the relative softness of the aluminum alloys.

The following procedure has been developed at the Naval Proving Ground and has been used in the metallographic preparation for the photomicrographs enclosed in this report:

(a) The specimen is removed from the plate material by sawing and given a preliminary polish on power driven abrasive belts.

(b) Polish grind on four successive lead laps charged with #180, #302, #303 1/2, and finally #305 grit, in the order noted. The laps are rotated at low speed, approximately 200 r.p.m.

(c) Polish grind on a wax wheel charged with #305 grit and soap solution. Use low speed as in (b) above.

(d) Final polish on Selvyt cloth charged with #3 levigated alumina. Use low speed as in (b) above.

(e) Etch and repolish as in (d) but with wheel stationary, specimen being moved by hand. Final etch for examination.

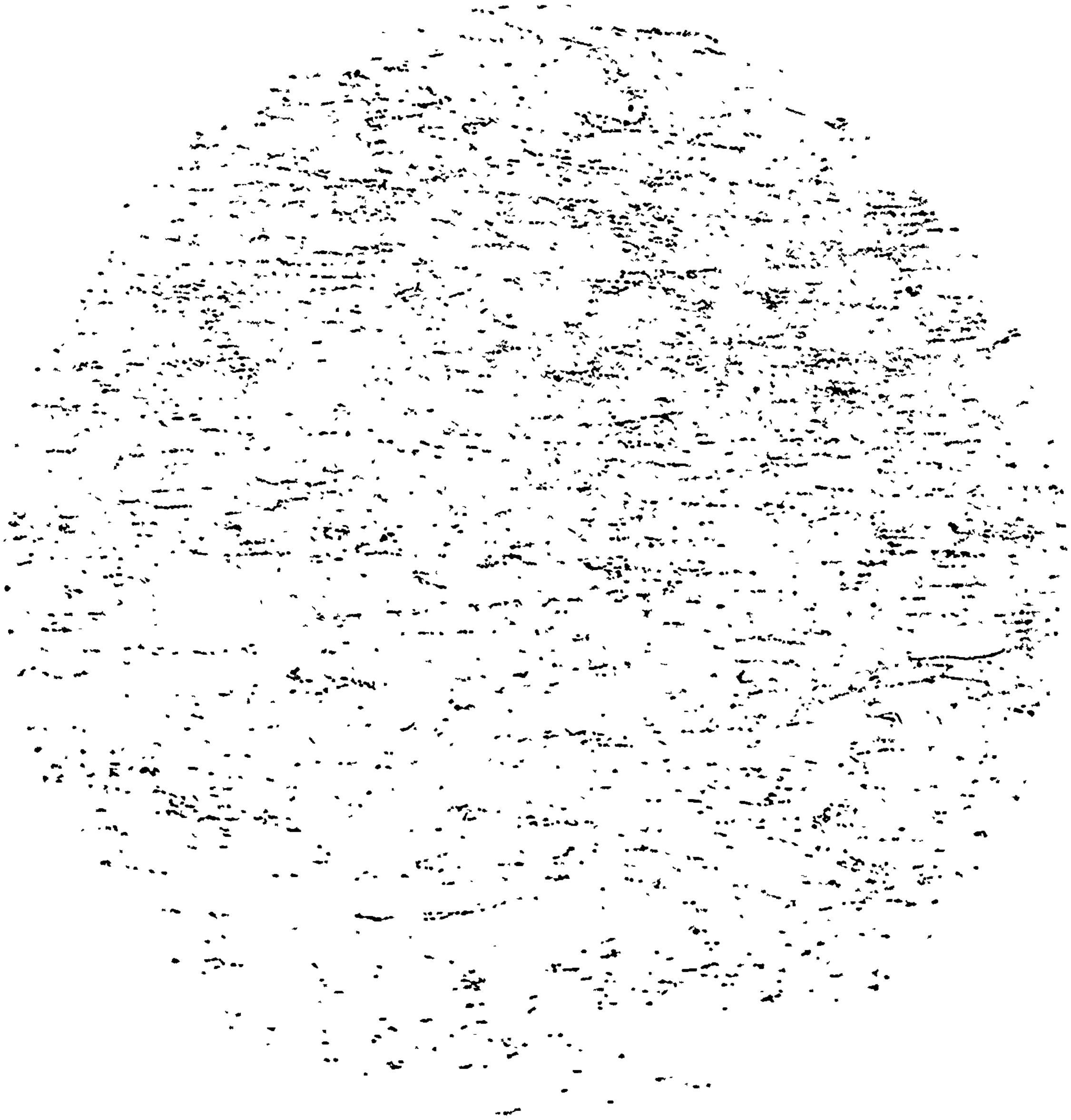
RESULTS OF METALLOGRAPHIC STUDY

A group of representative photomicrographs of the subject alloys are appended to this report. This group has been selected to show the most important characteristics of the alloys. Only the photomicrographs of the 3/4" and 1 1/2" plates are presented. The photomicrographs of the 1 1/4" plates have been omitted because their microstructure has been found to be intermediate to the 1 1/2" and 3/4" plates. The photomicrographs presented show the microstructure at the center position, on planes parallel and perpendicular to the surface of the plate. It should be noted that all alloys show a decided difference in the appearance of the microstructure on planes perpendicular, as compared to planes parallel to the plate surface.

The appearance of the microstructure in the direction parallel to rolling shows clearly the effect of continued rolling from 1 1/2" to 3/4". The microstructure of the 1 1/2" plates, which is remarkably similar to that of a cast material, shows a considerable change when the plate is rolled to 3/4". At this gauge the cast structure, exemplified by the continuous networks of eutectic constituents, is partially or completely broken up depending on the specific alloy under consideration. It is believed that the superiority of the 3/4" plates, both in mechanical properties and in ballistic quality, is due to this improvement in the microstructure of the alloys. It is generally known that brittle constituents in a continuous or semi-continuous networks will impart their deficiencies to the material out of all proportion to their volume relation to the matrix material.

The identification of the constituents of aluminum alloys is usually a very complicated and difficult procedure because of the complexity of the analyses. An attempt has been made to note the specific types of constituents which are present in the subject alloys for purposes of record. However, the properties of these constituents are not well known.

The presence of cold worked grains in the alloy 24S-T80 should be noted. In accordance with the alloy identification methods outlined in the first section this alloy should not



ALLOY: 61S-T ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: 2.5% HF, 10.0% HCl

Aluminum alloy matrix with elongated grains showing the effect of rolling. The relatively low alloy composition prevents development of grain contrast by etching.

MAGI

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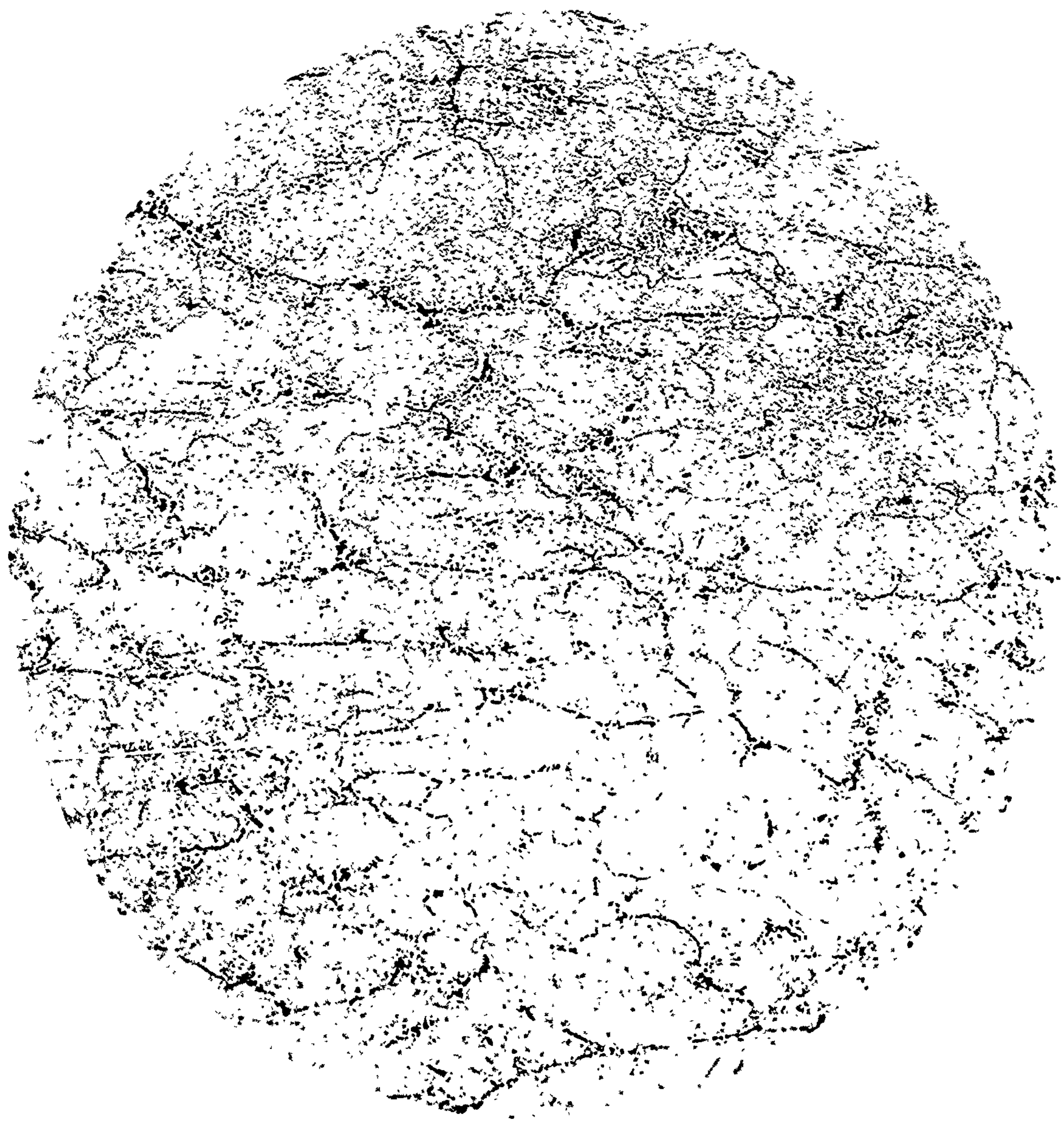
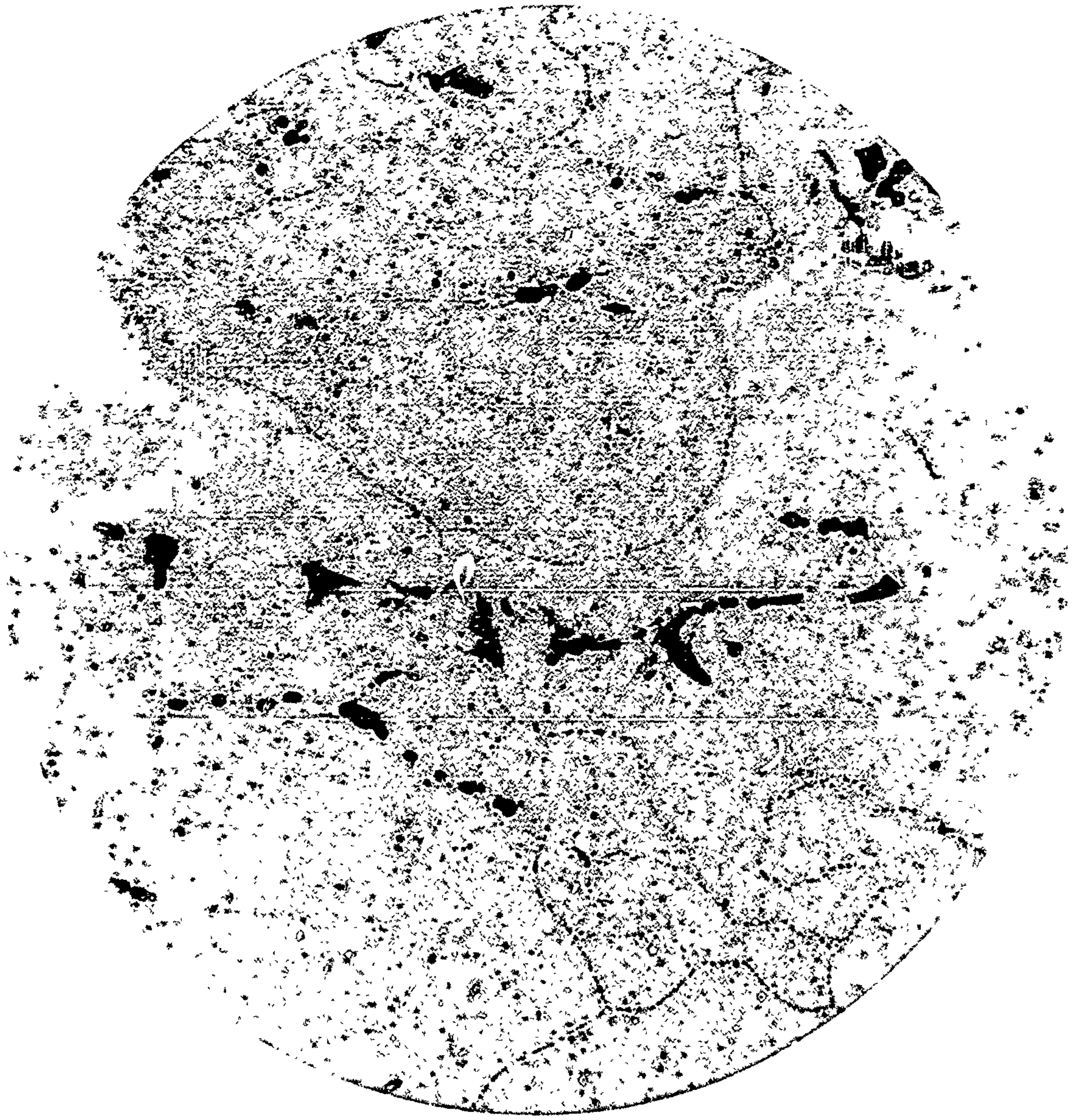


ALLOY: 61S-T ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 100X ETCH: 2.5% HF, 10.0% HCl

Aluminum alloy matrix showing a continuous network of constituents laid down during freezing. The rolling operation has been unsuccessful in breaking up this pattern.

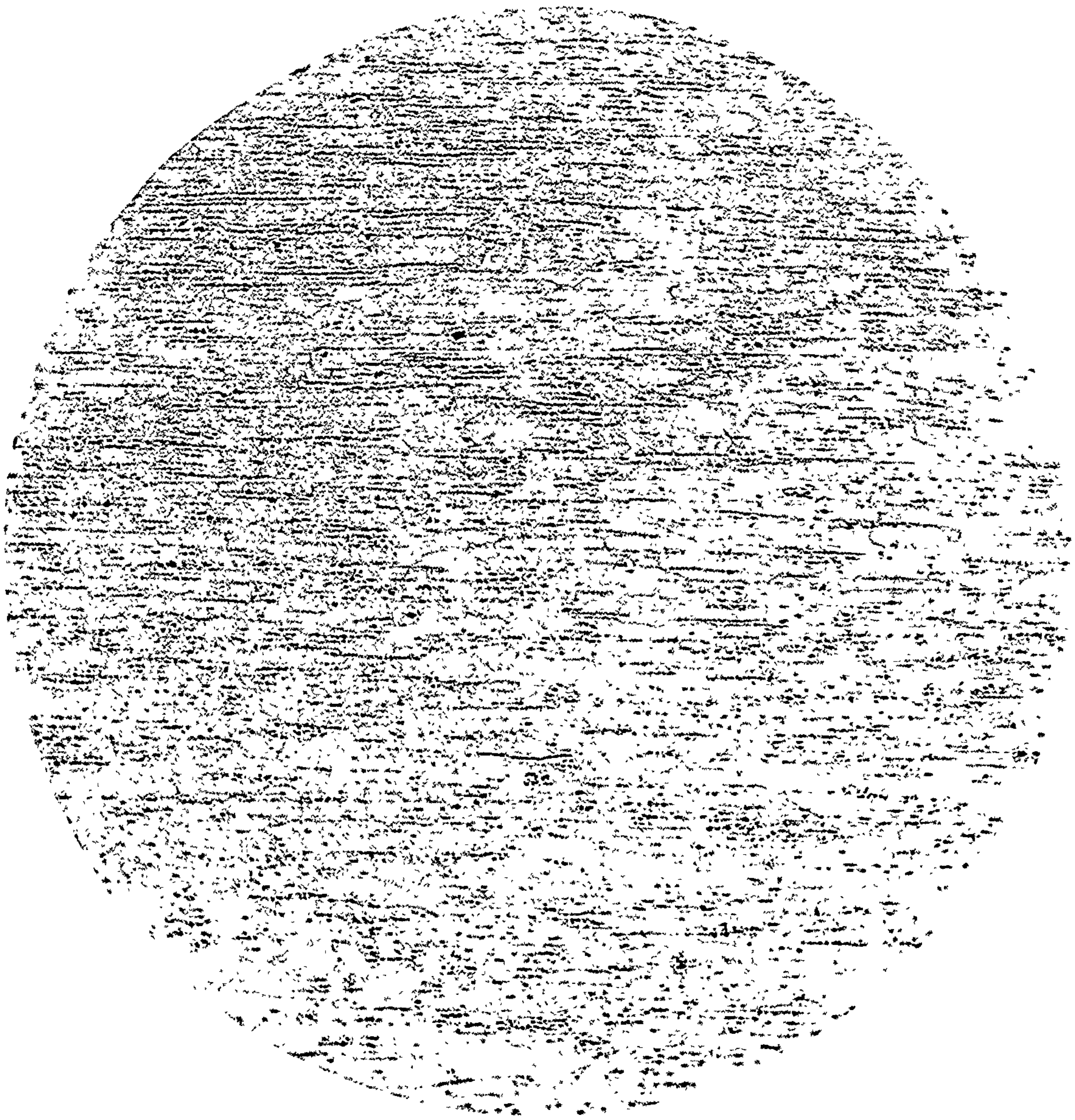


ALLOY: 61S-T ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: 2.5% HF, 10.0% HCl

Aluminum alloy matrix showing network particles of Al-Cu-Si-Fe constituents and grain boundary precipitates (possibly $CuAl_2$).

of rolling. The relatively low alloy composition prevents
development of grain contrast by etching.

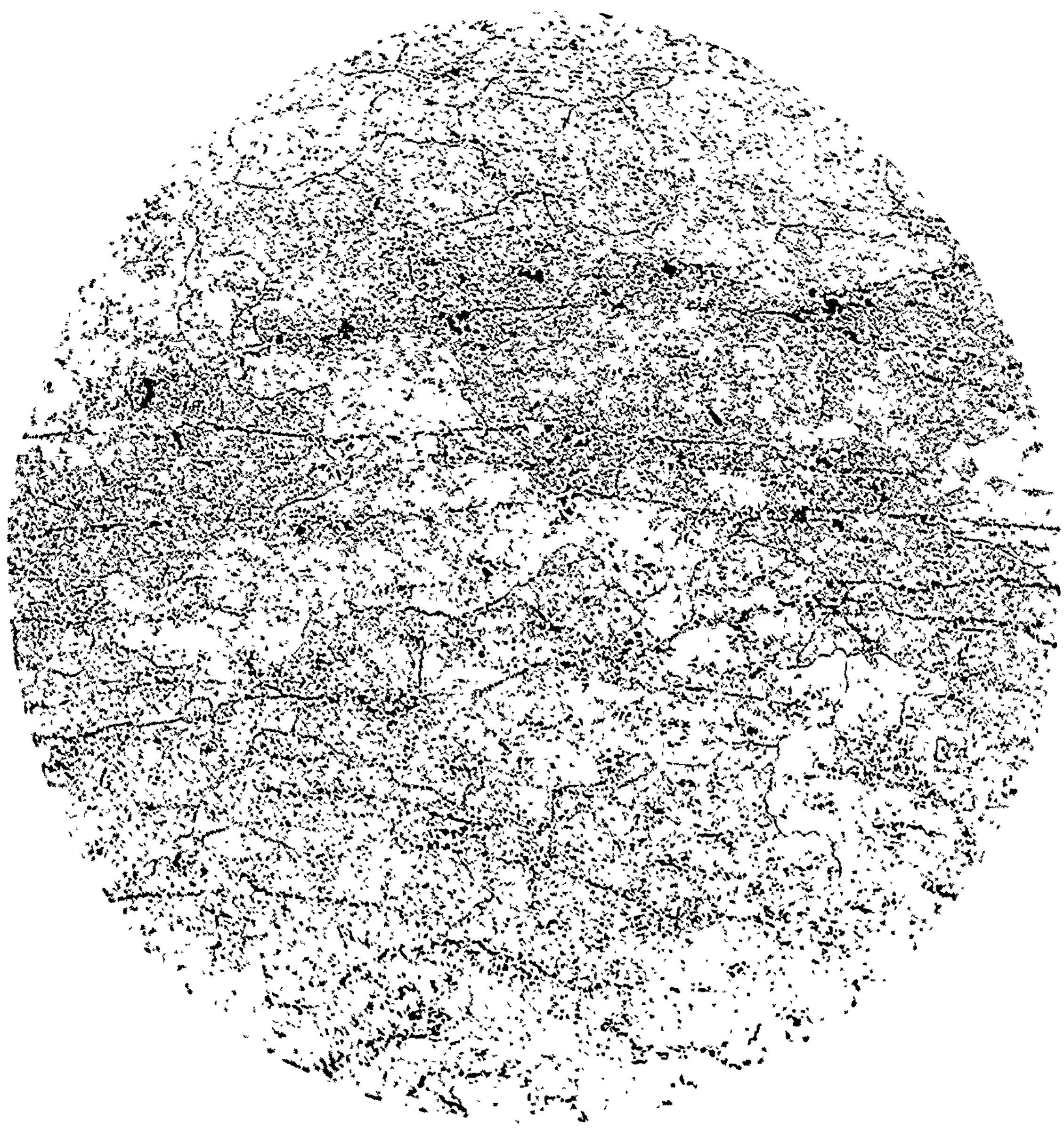


ALLOY: 61S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: 2.5% HF, 10.0% HCl

Aluminum alloy matrix with elongated grains showing the effect of rolling. The relatively low alloy composition prevents development of grain contrast by etching.

Aluminum alloy ma
stituents laid down during freezing. The rolling operation has been unsuccessful in breaking up this pattern.

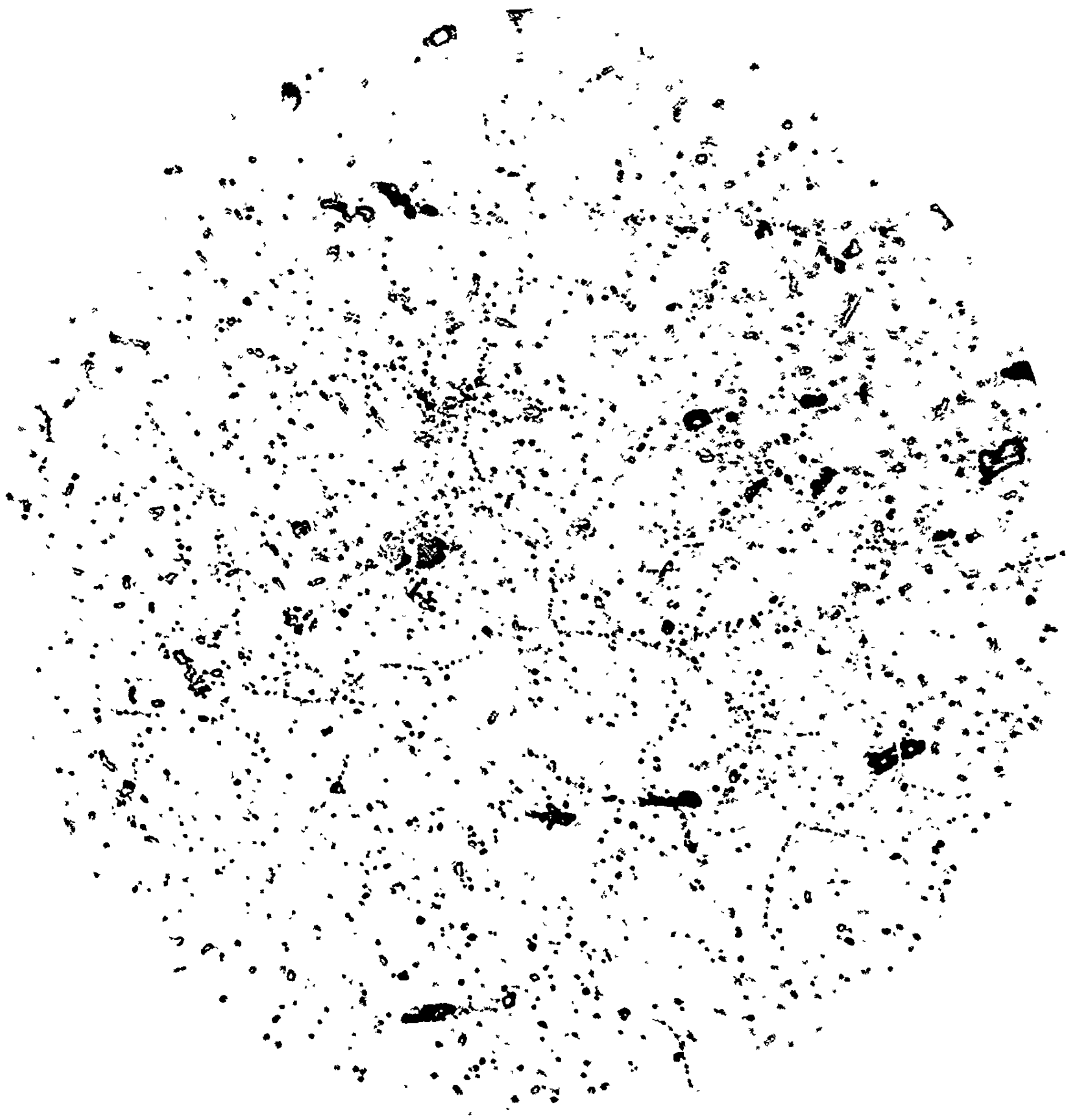


ALLOY: 61S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 100X ETCH: 2.5% HF, 10.0% HCl

Aluminum alloy matrix showing that the continuous network present in the 1-1/2" plate has been partially broken up by continued rolling.

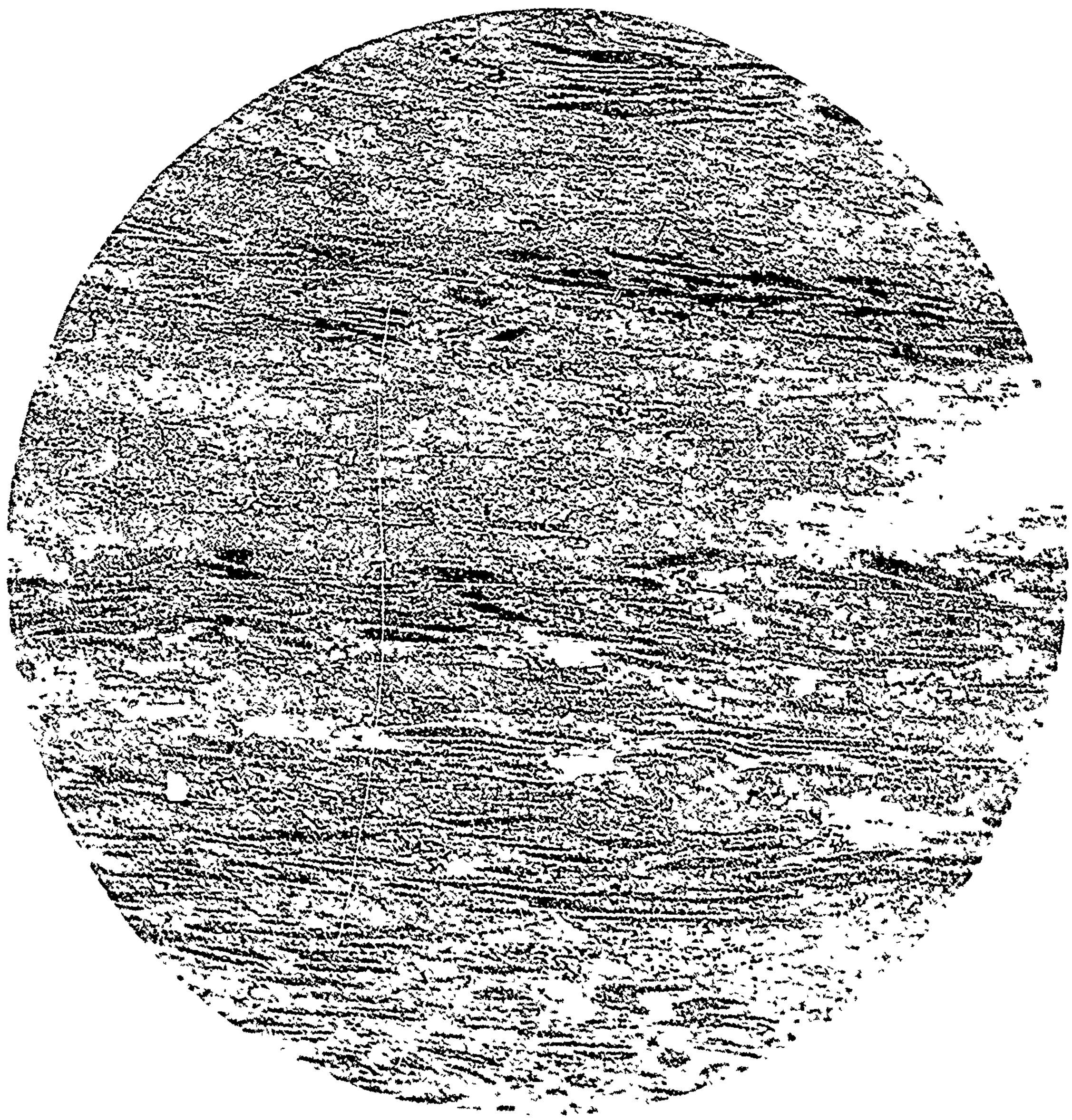
Aluminum alloy matrix showing network particles of Al-Cu-Si-Fe constituents and grain boundary precipitates (possibly $CuAl_2$).



ALLOY: 61S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: 2.5% HF, 10.0% HCl

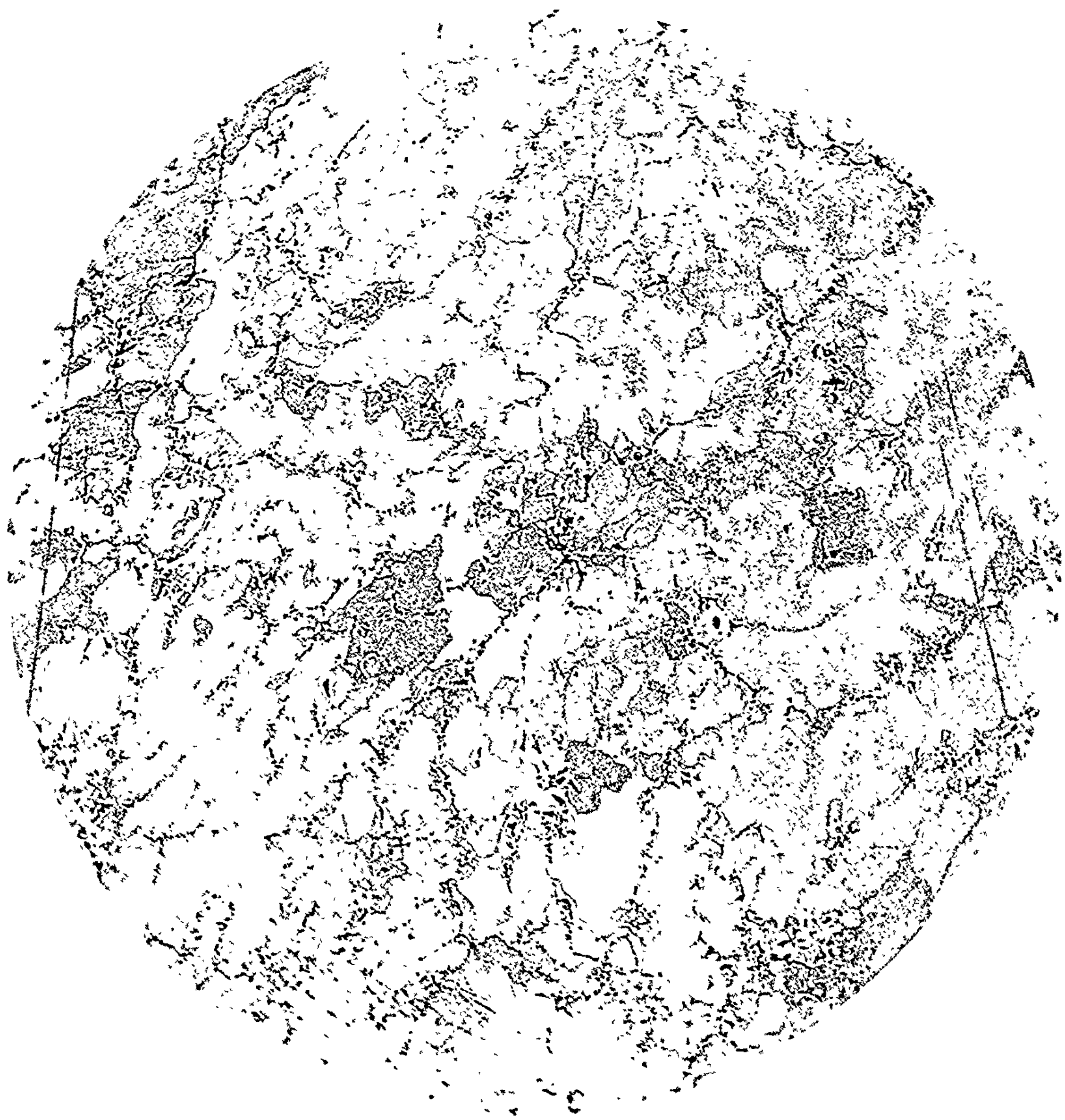
Aluminum alloy matrix showing scattered particles of Al-Cu-Si-Fe constituents and grain boundary precipitates (possibly $CuAl_2$).



ALLOY: 24S-T (ALCOA)
PLATE: 1-1/2" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

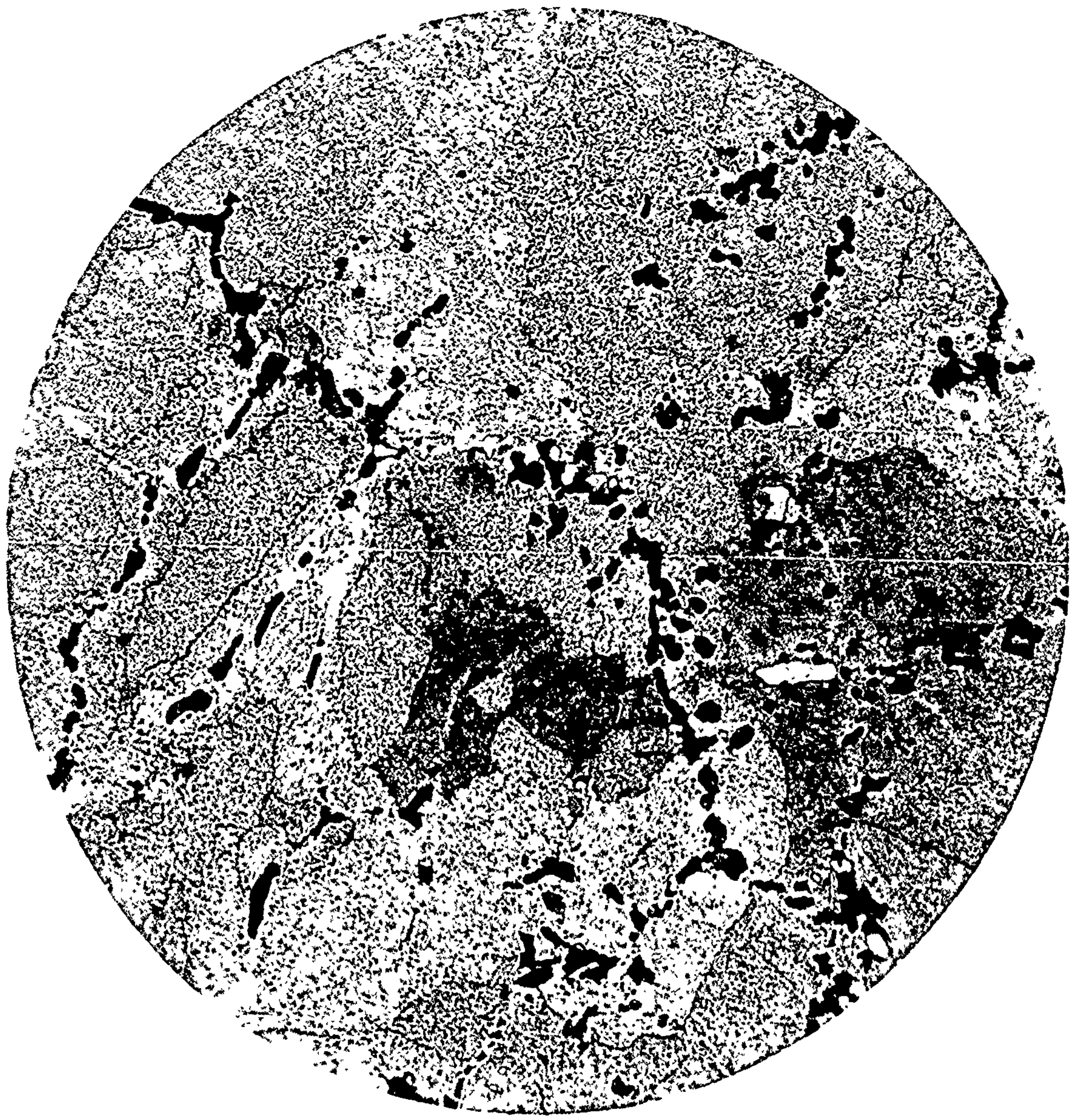
Aluminum alloy matrix with elongated grains showing the effect of rolling. The dark etching wavy patches represent regions which have not been sufficiently homogenized to eliminate the effect of coring.



ALLOY: 24S-T (ALCOA)
PLATE: 1-1/2" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

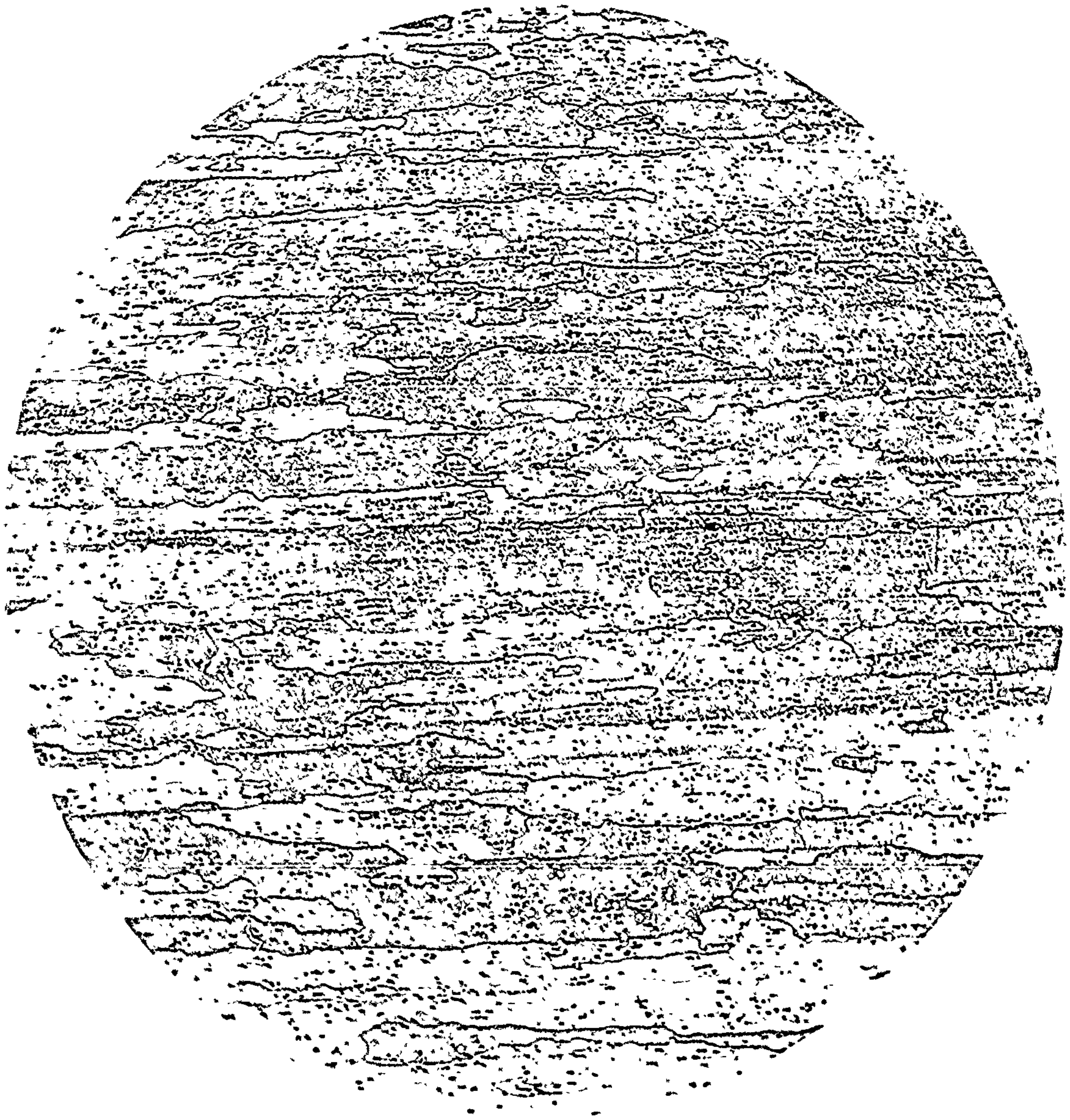
Aluminum alloy matrix showing a semi-continuous network of constituents laid down during freezing. The rolling operation has been unsuccessful in breaking up this pattern.



ALLOY: 24S-T (ALCOA)
PLATE: 1-1/2" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

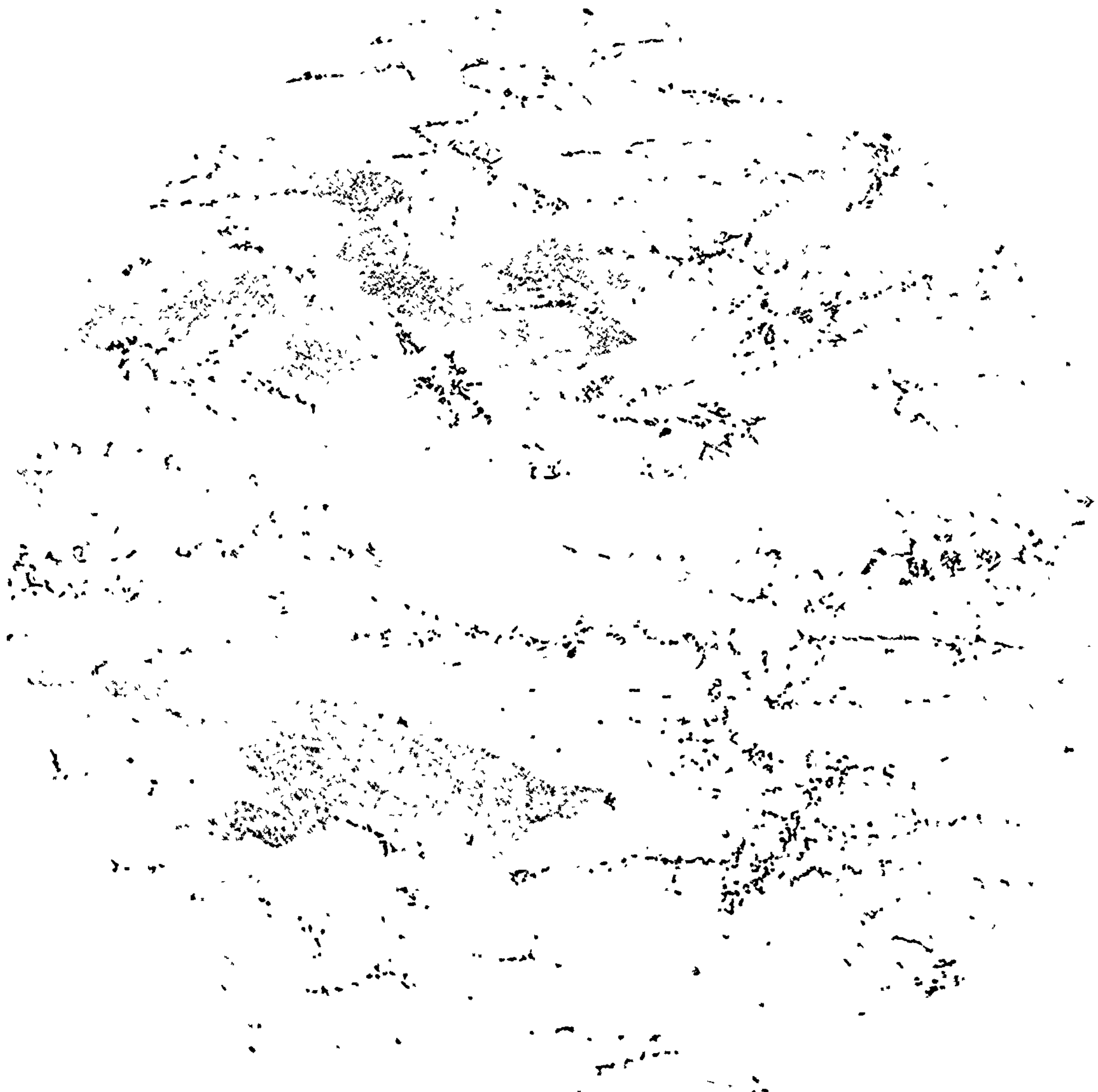
Aluminum alloy matrix showing a semi-continuous network of Al-Cu-Fe-Mn and $CuAl_2$ constituents.



ALLOY: 24S-T (ALCOA)
PLATE: 3/4" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix with elongated grains showing the effect of rolling. Note the homogeneous appearance of this structure in comparison to that of the 1-1/2" plate.



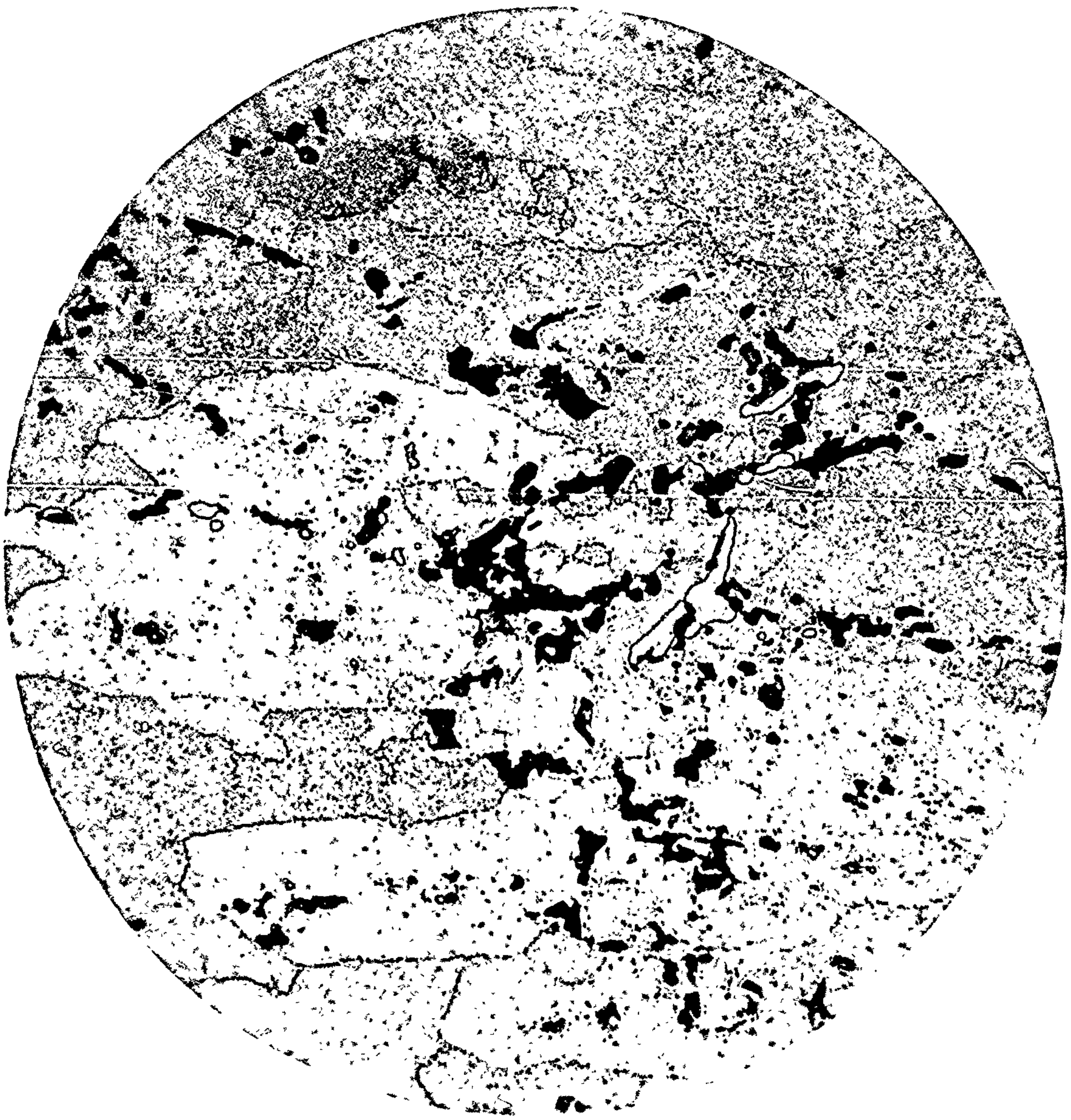
ALLOY: 24S-T (ALCOA)
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

'ace.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix showing that the cast pattern appearing in the 1-1/2" plate has been broken up by the continued rolling. Note the region contrast.

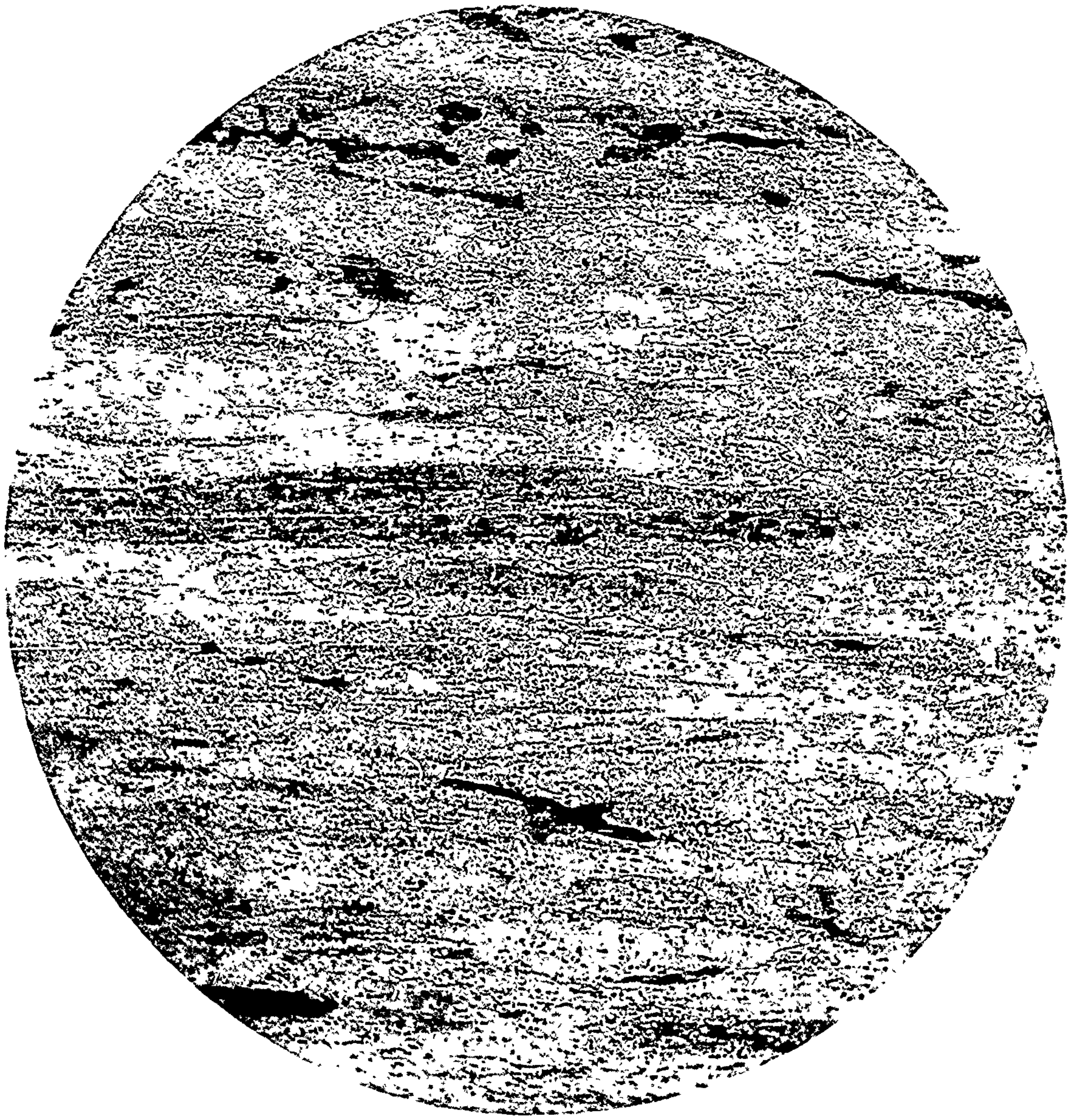
Al-Cu-Fe-Mn and $CuAl_2$ constituents.



ALLOY: 24S-T (ALCOA)
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

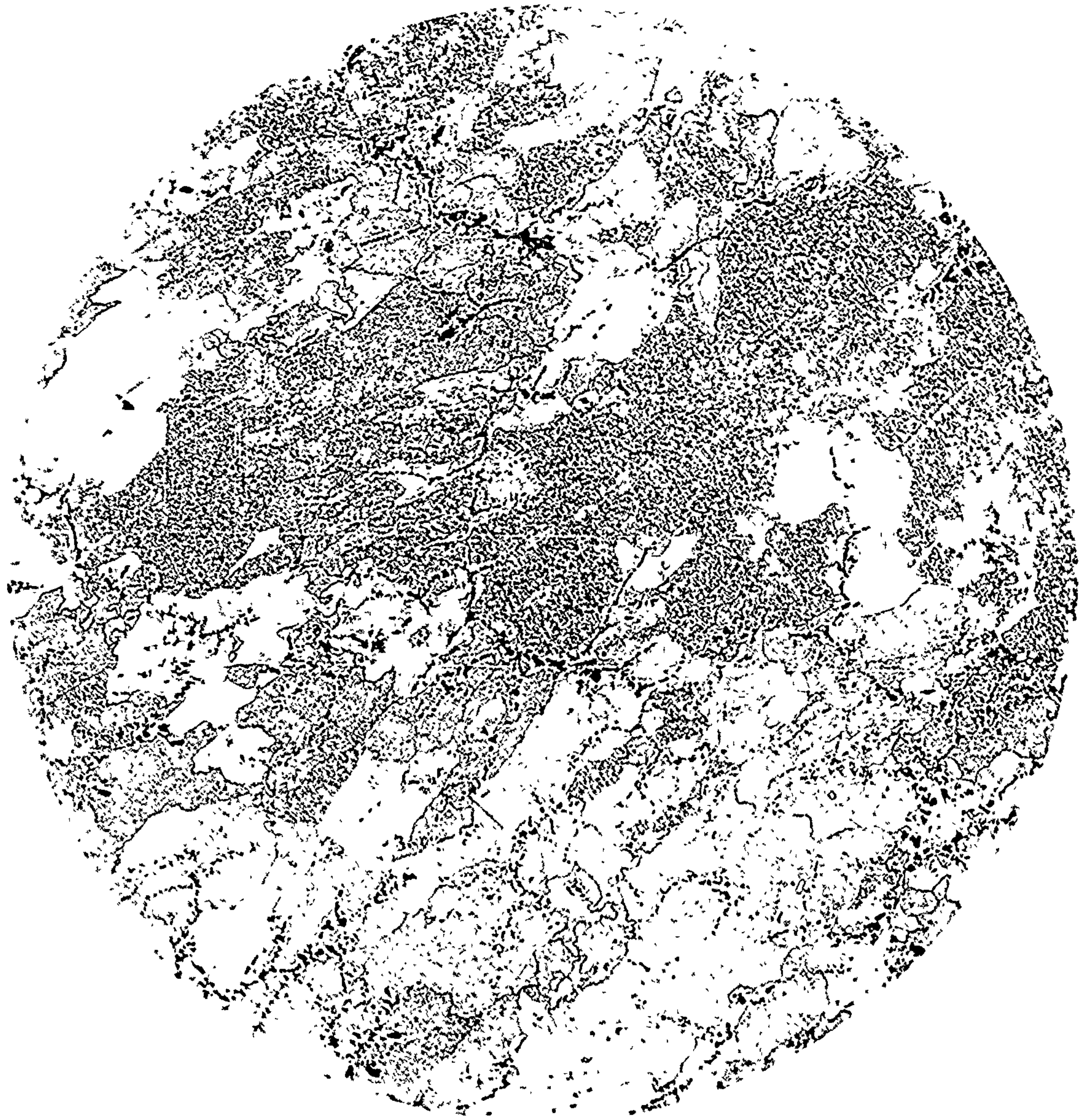
Aluminum alloy matrix showing scattered particles of Al-Cu-Fe-Mn and $CuAl_2$ constituents.



ALLOY: 24S-T80 ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

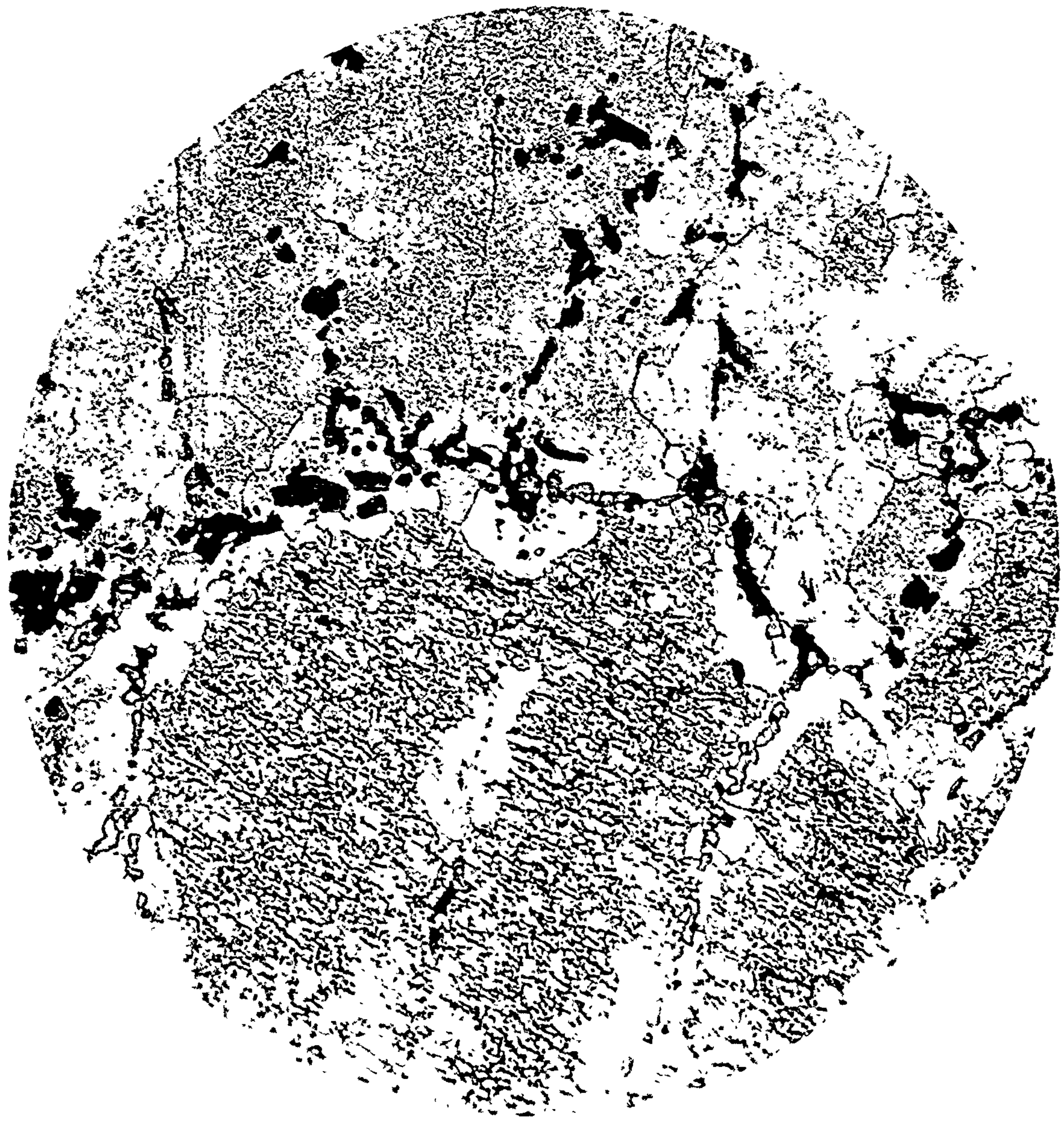
Matrix of aluminum alloy with elongated grains showing the effect of rolling. The dark etching patches are cold worked grains.



ALLOY: 24S-T80 ALCOA
PLATE: 1-1/2" GAUGE
SECTION At center on plane parallel to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

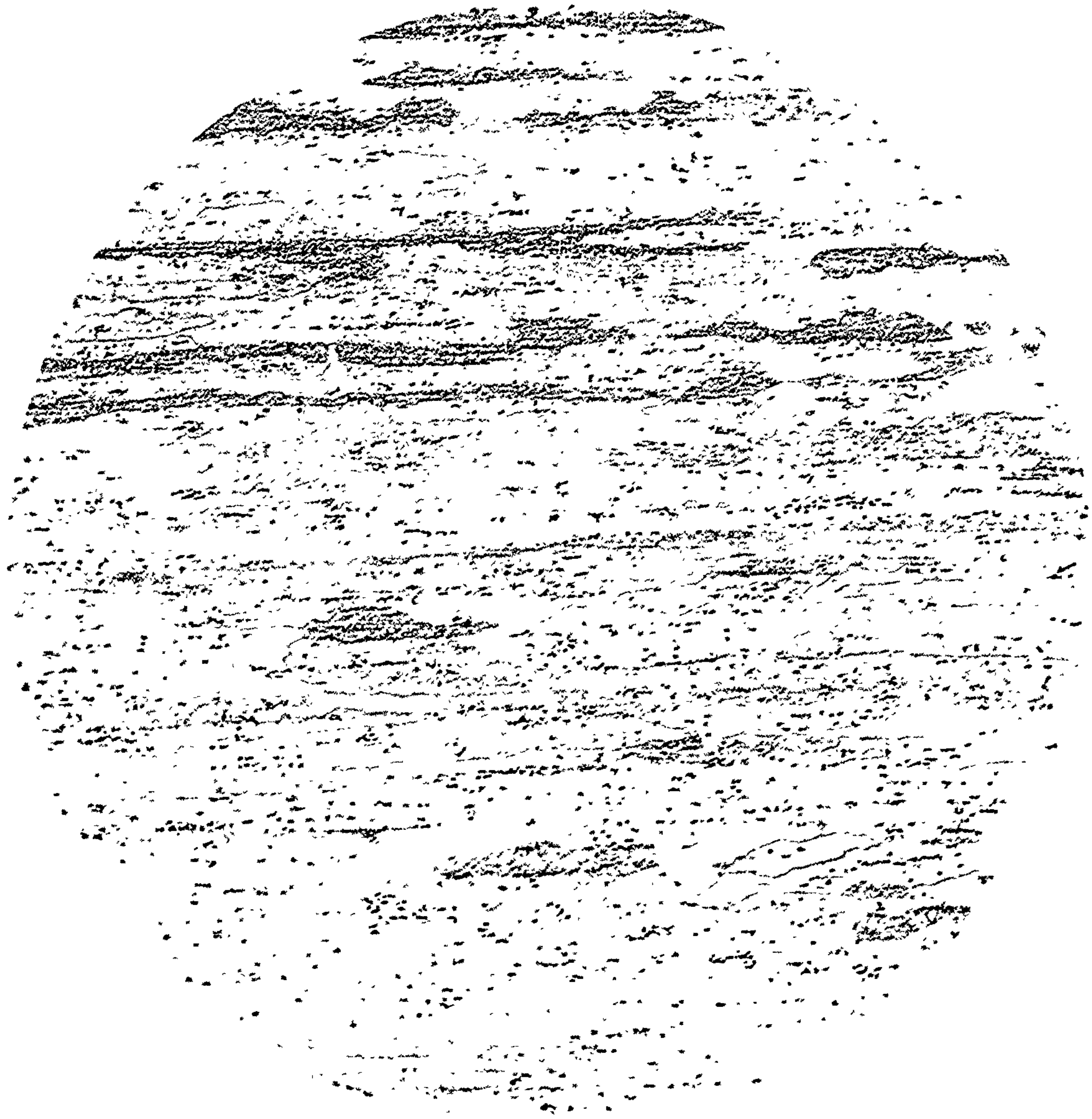
Matrix of aluminum alloy showing cold worked grains and a semi-continuous network of constituents in the pattern laid down during freezing. The rolling operation has been unsuccessful in breaking up this pattern.



ALLOY: 24S-T80 ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Matrix of aluminum alloy showing cold worked grains and a semi-continuous network of Al-Cu-Fe-Mn and $CuAl_2$ constituents.

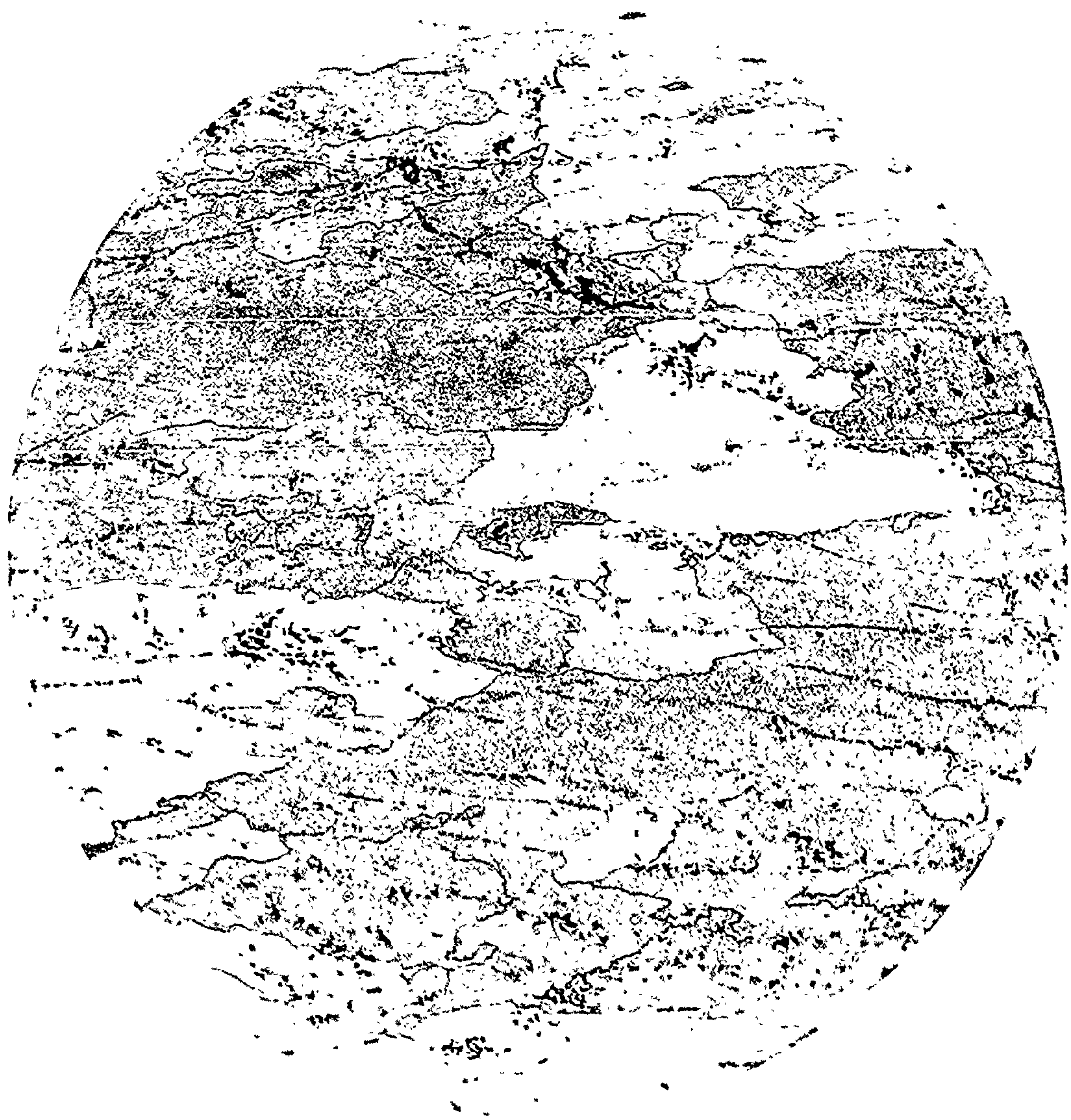


ALLOY: 24S-T80 ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Matrix of aluminum alloy with elongated grains showing the effect of rolling. The dark etching patches are cold worked grains. Note that the woody laminated pattern is more pronounced than in the 1-1/2" plate.

laid down during freezing. The rolling operation has been unsuccessful in breaking up this pattern.



urface.

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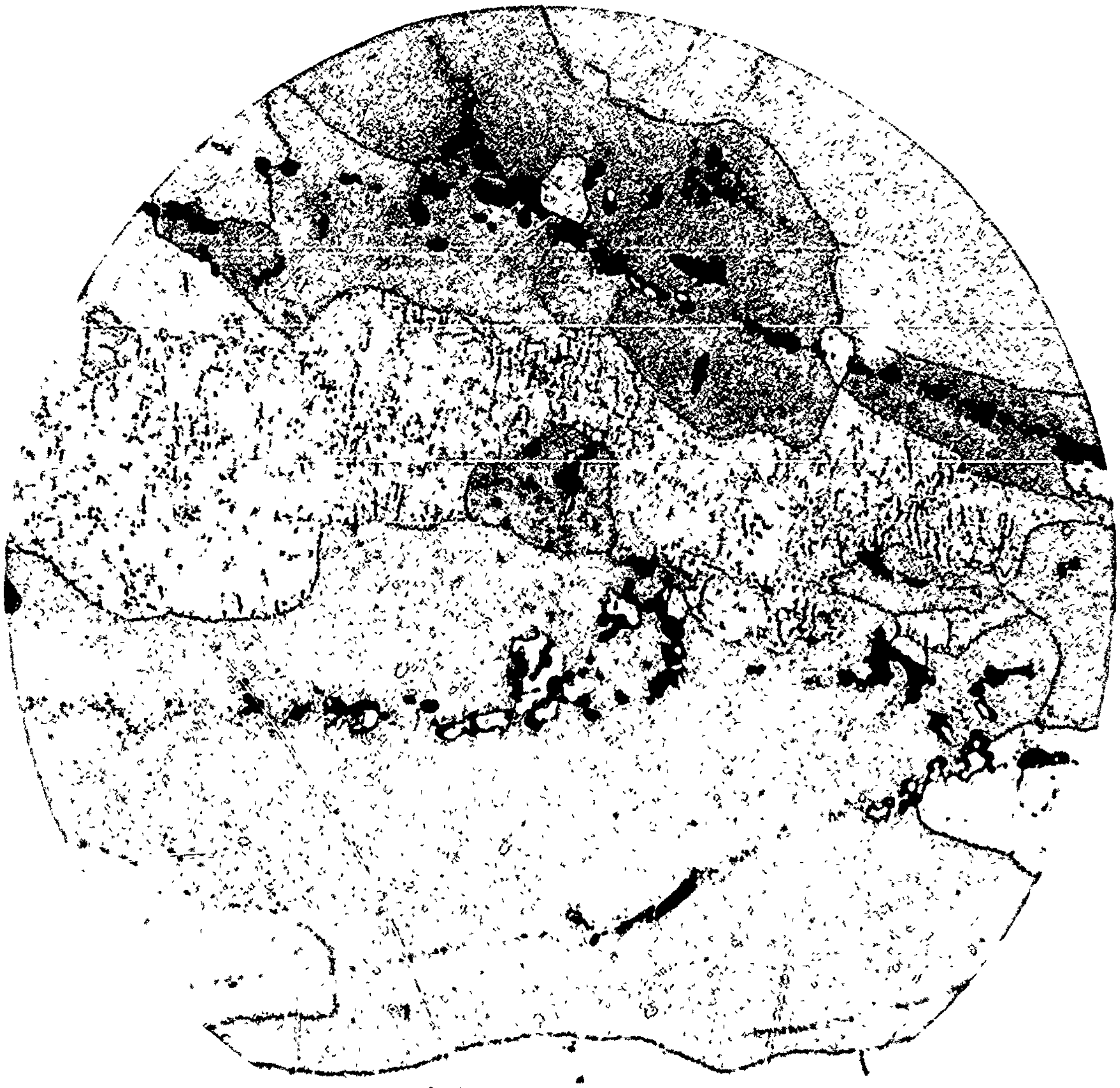
**ALLOY:** **24S-T80 ALCOA**
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Matrix of aluminum alloy showing that the cast pattern appearing in the 1-1/2" plates has been broken up by continued rolling. Note grain contrast occasioned by chemical heterogeneity.

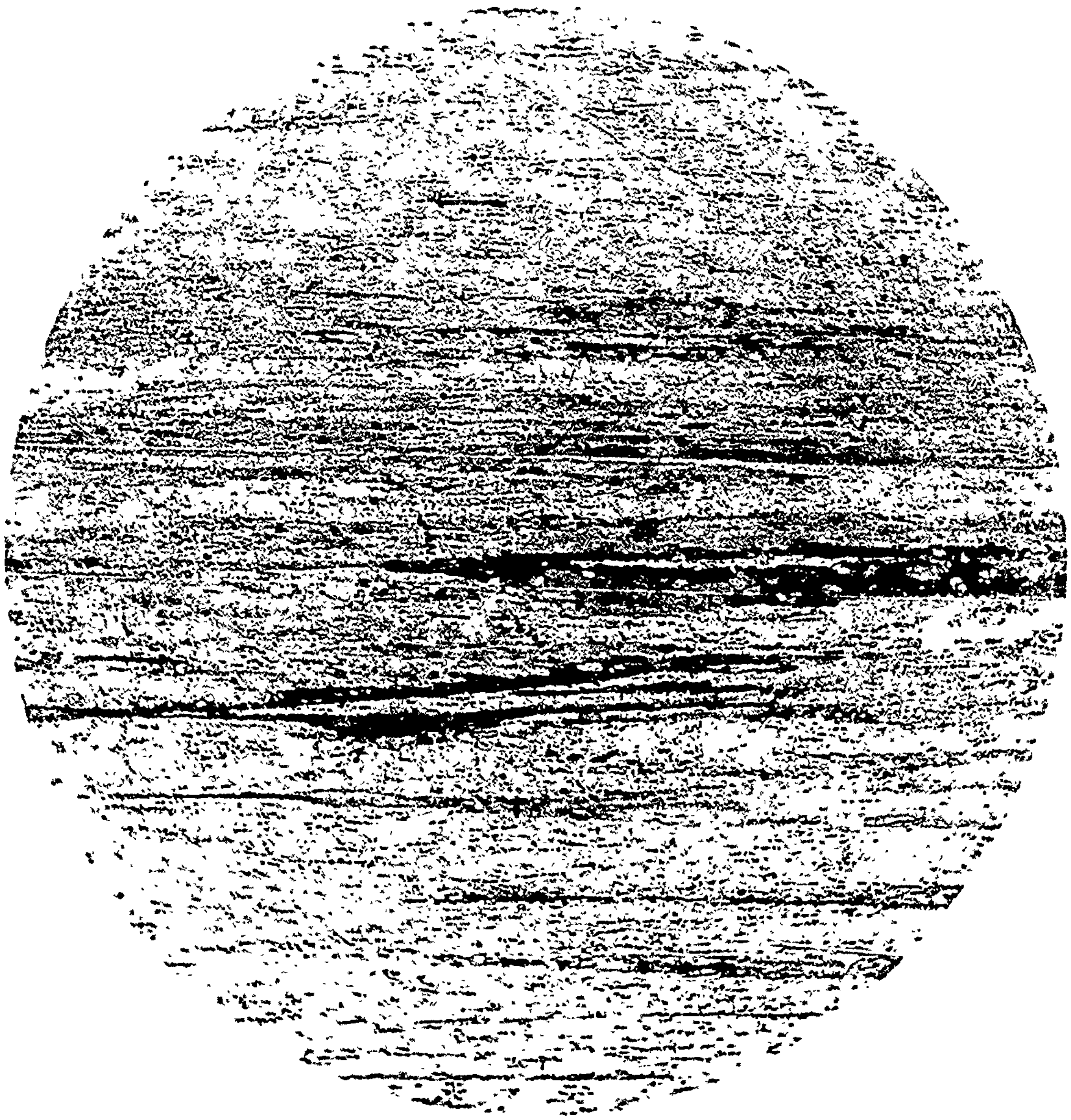
continuous network of Al-Cu-Fe-Mn and $CuAl_2$ constituents.



ALLOY: 24S-T80 ALCOA
PLATE: 3/4" GAUGE
SECTION At center on plane parallel to surface.

MAGN: 500X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

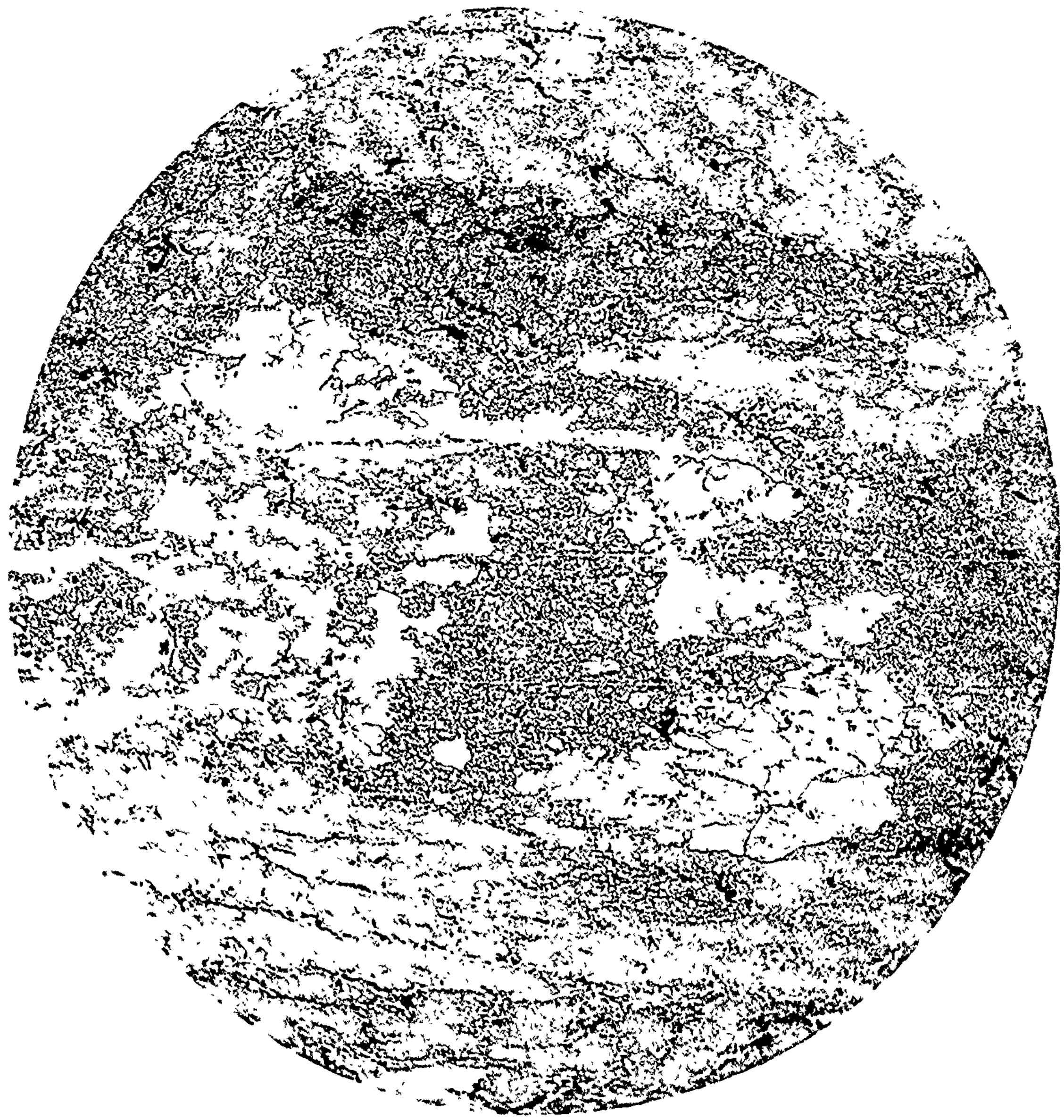
Matrix of aluminum alloy showing scattered particles of Al-Cu-Fe-Mn and $CuAl_2$ constituents. Note cold worked again.



ALLOY: 14S-T ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

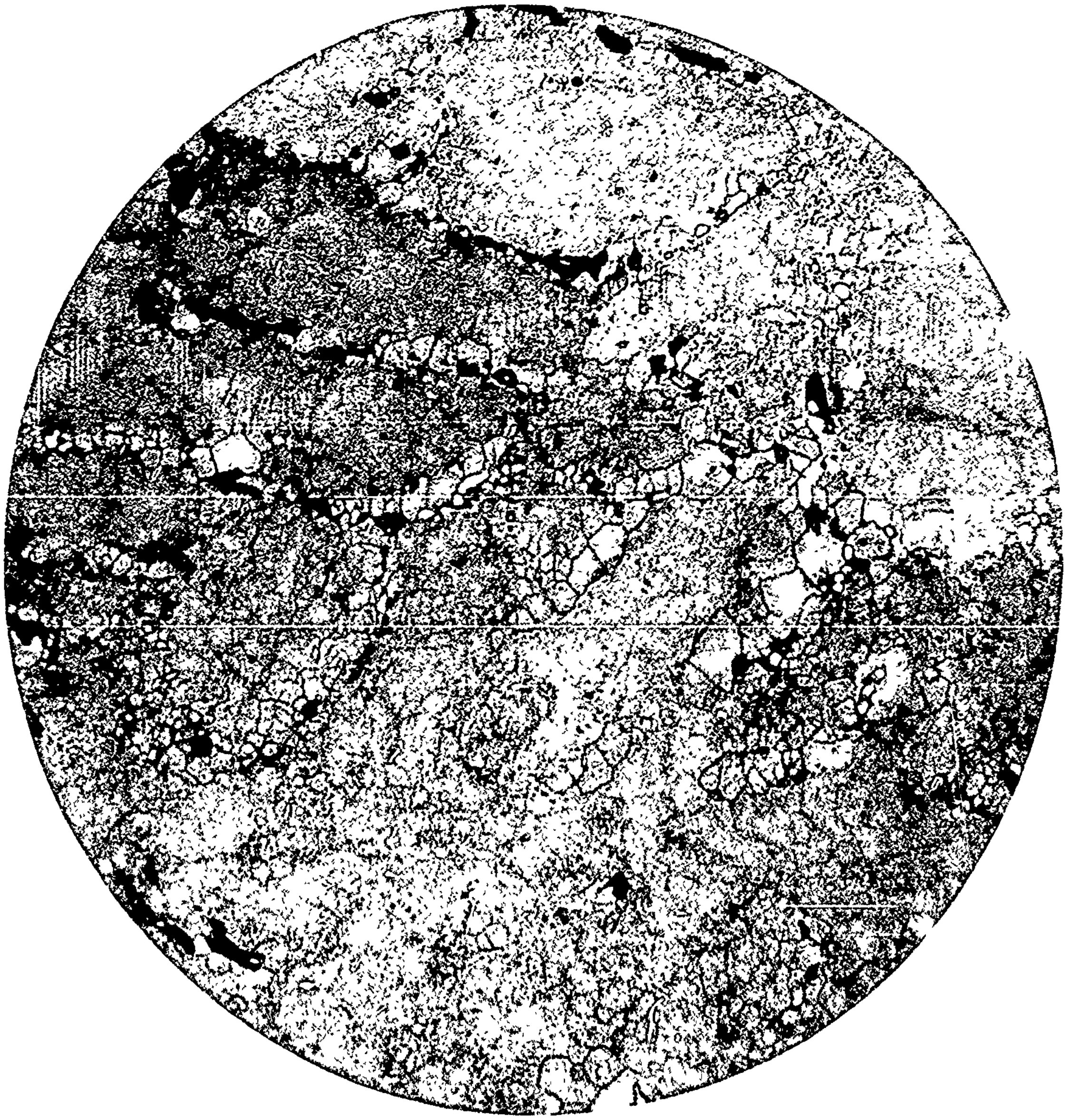
Aluminum alloy matrix with elongated grains showing the effect of rolling. The darker etching patches represent groupings of grains having a somewhat higher alloy compositions than the surrounding matrix.



ALLOY: 14S-T ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 100X  ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

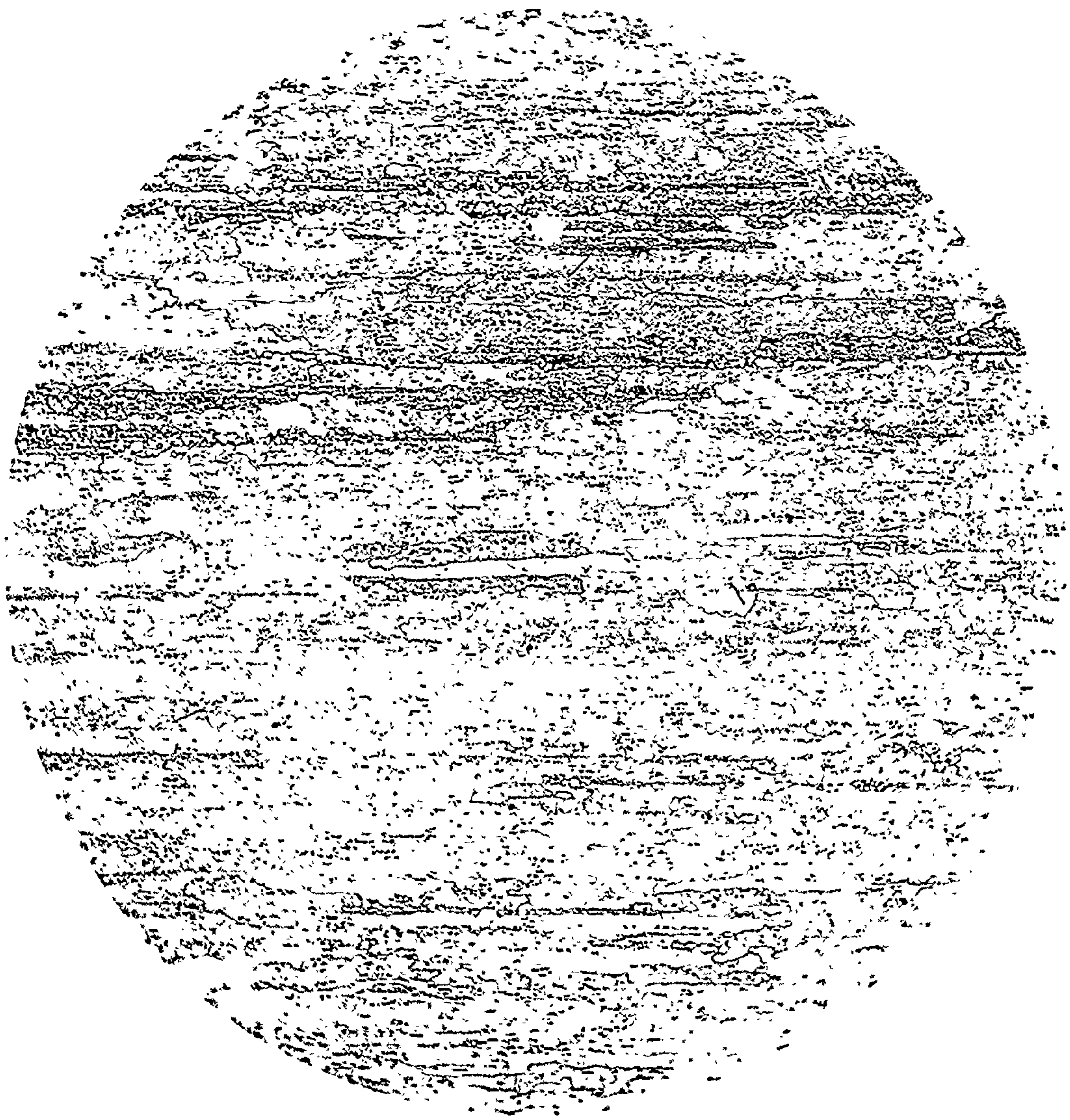
Aluminum alloy matrix showing a semi-continuous network of constituents laid down at freezing. The rolling operation has been unsuccessful in breaking up the cast pattern. Note the grain contrast (region contrast) occasioned by chemical heterogeneity.



ALLOY: 14S-T ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix showing a fine recrystallized grain structure and a semi-continuous network of Al-Cu-Si-Fe and $CuAl_2$ constituents.

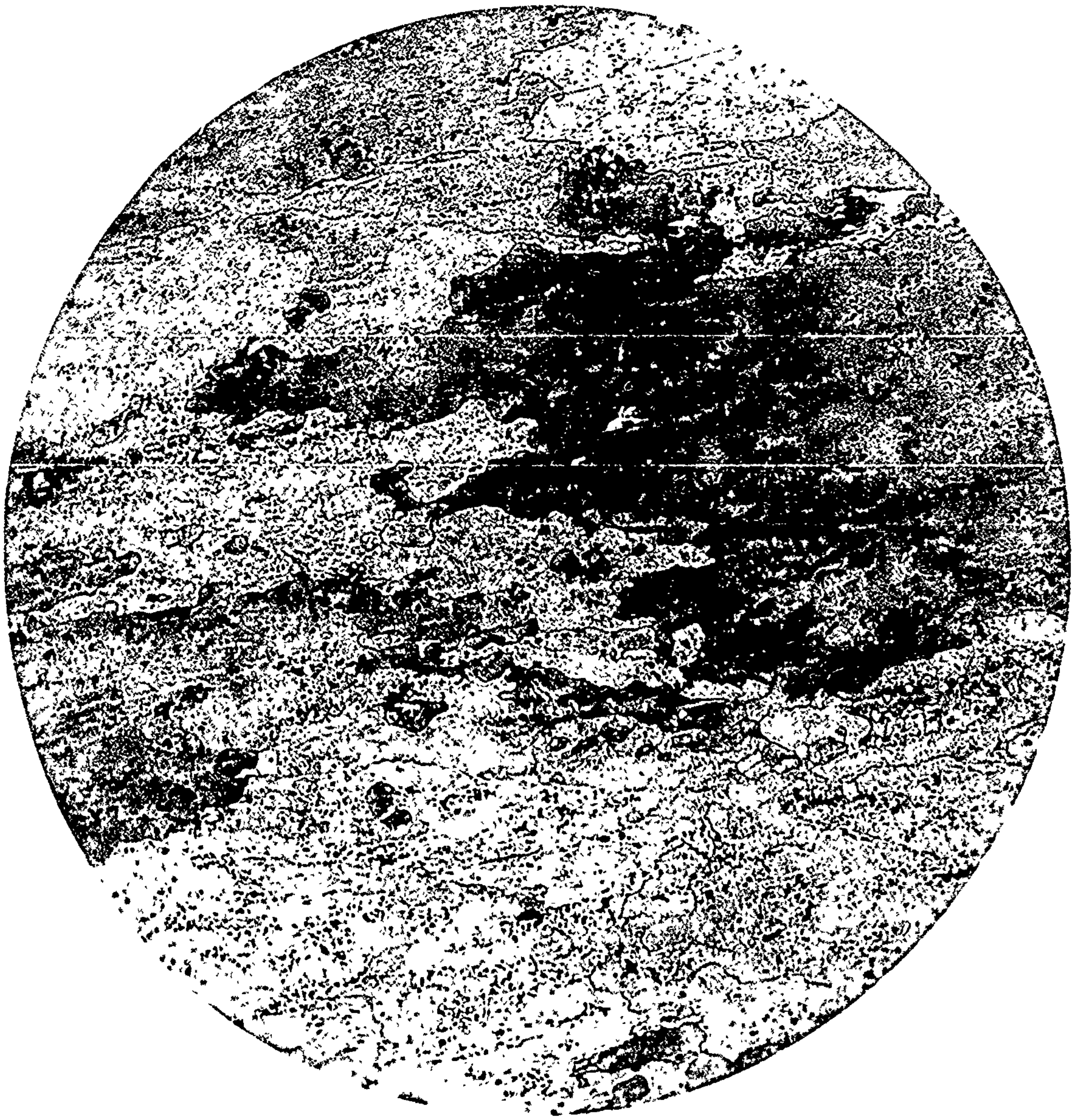


ALLOY: 14S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on a plane perpendicular to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix with elongated grains showing the effect of rolling. The darker etching patches represent groupings of grains have a somewhat higher alloy composition than the surrounding matrix.

Note the grain contrast (region contrast) occasioned by chemical heterogeneity.



face.

ALLOY: 14S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

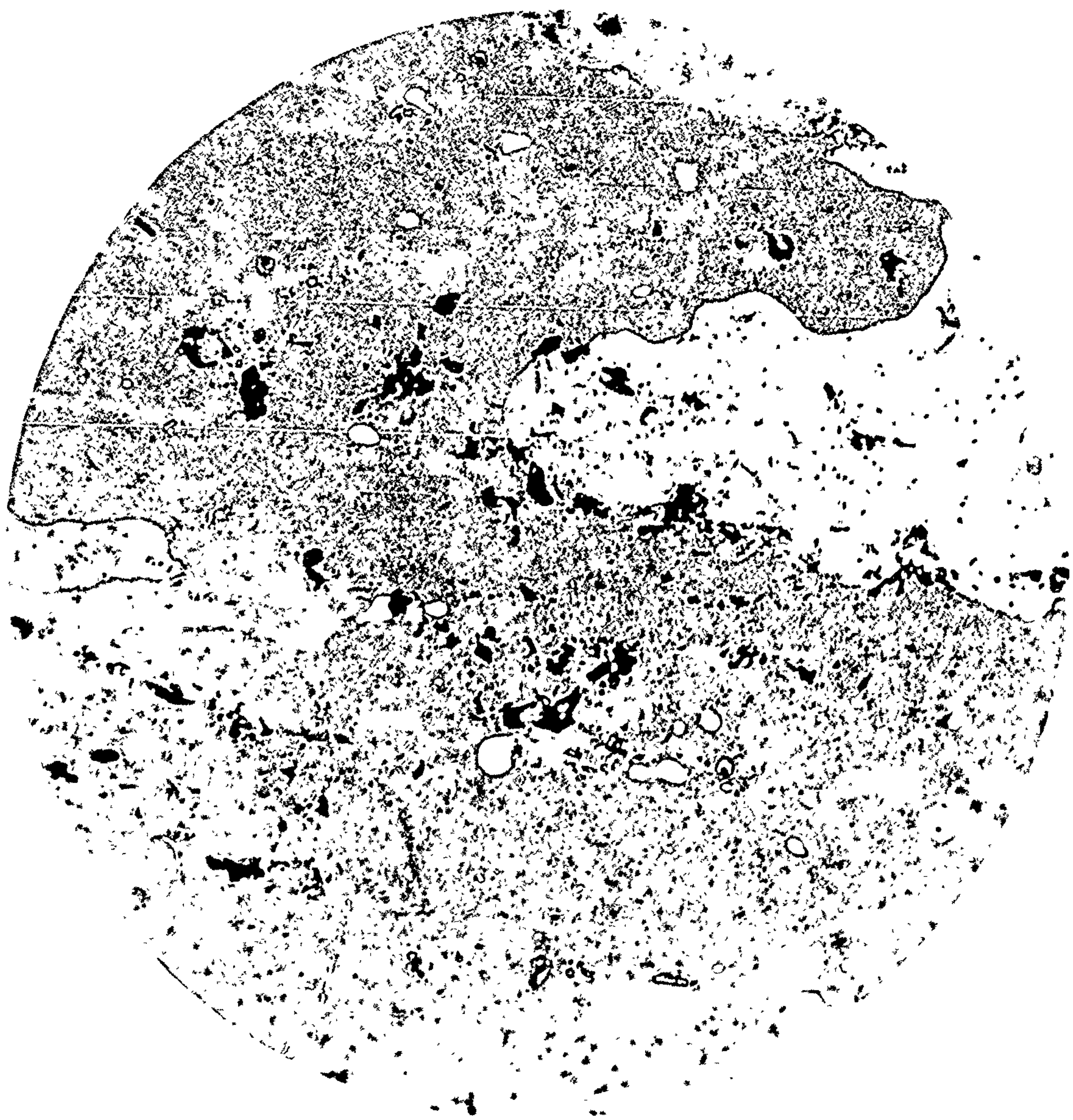
MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix showing that network of constituents laid down at freezing has been broken up by continued rolling. Note the region etching contrast occasioned by chemical heterogeneity.

MA

Al
Fe

Aluminum alloy matr[illegible]
structure and a semi-continuous network of Al-Cu-Si-Fe and $CuAl_2$ constituents.



ALLOY: 14S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix showing scattered particles of Al-Cu-Si-Fe and $CuAl_2$ constituents.

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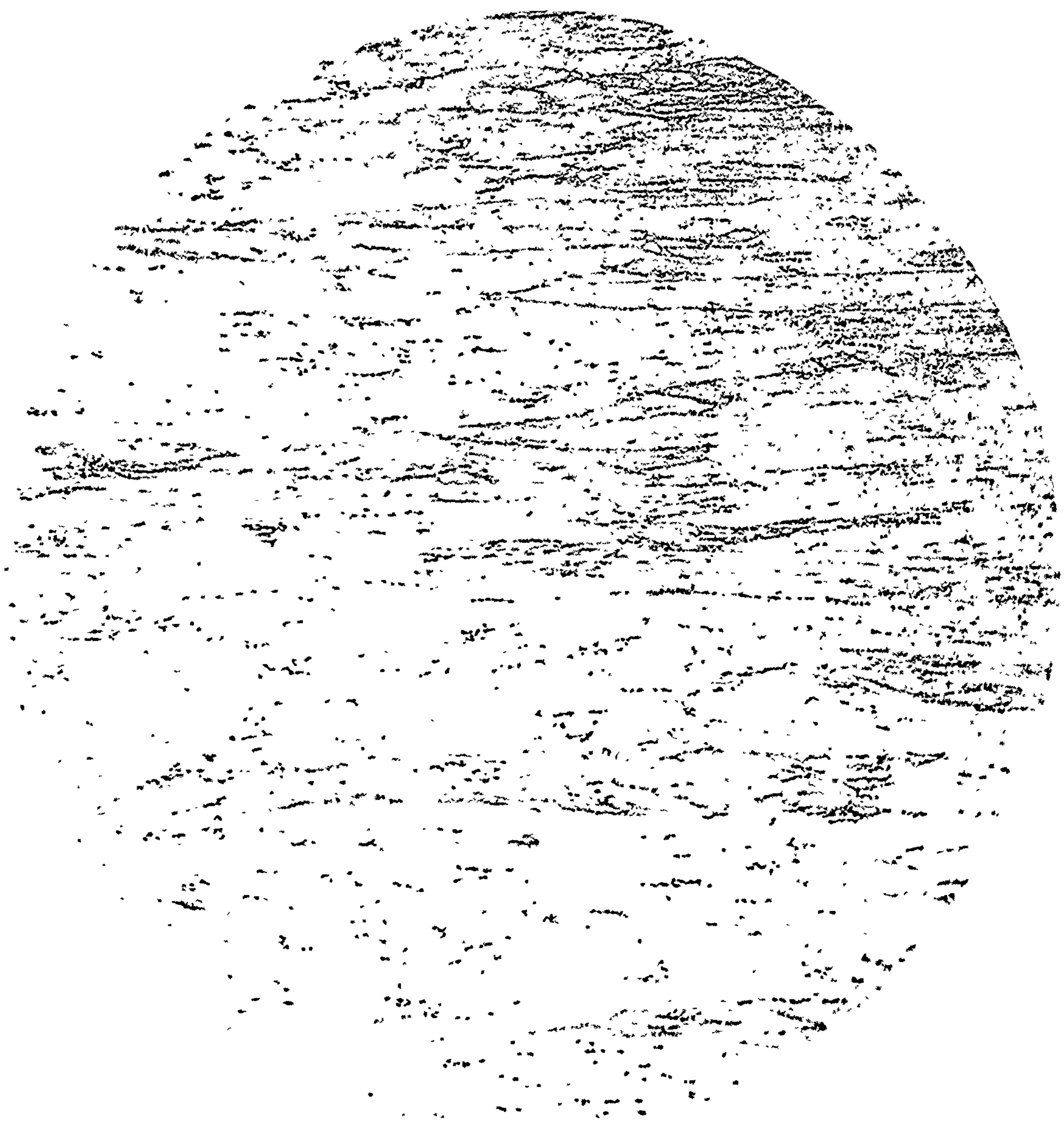


ALLOY: 75S-T ALCOA
PLATE: 1-1/2" GAUGE
SECTION: At center on plane perpendicular to surface.

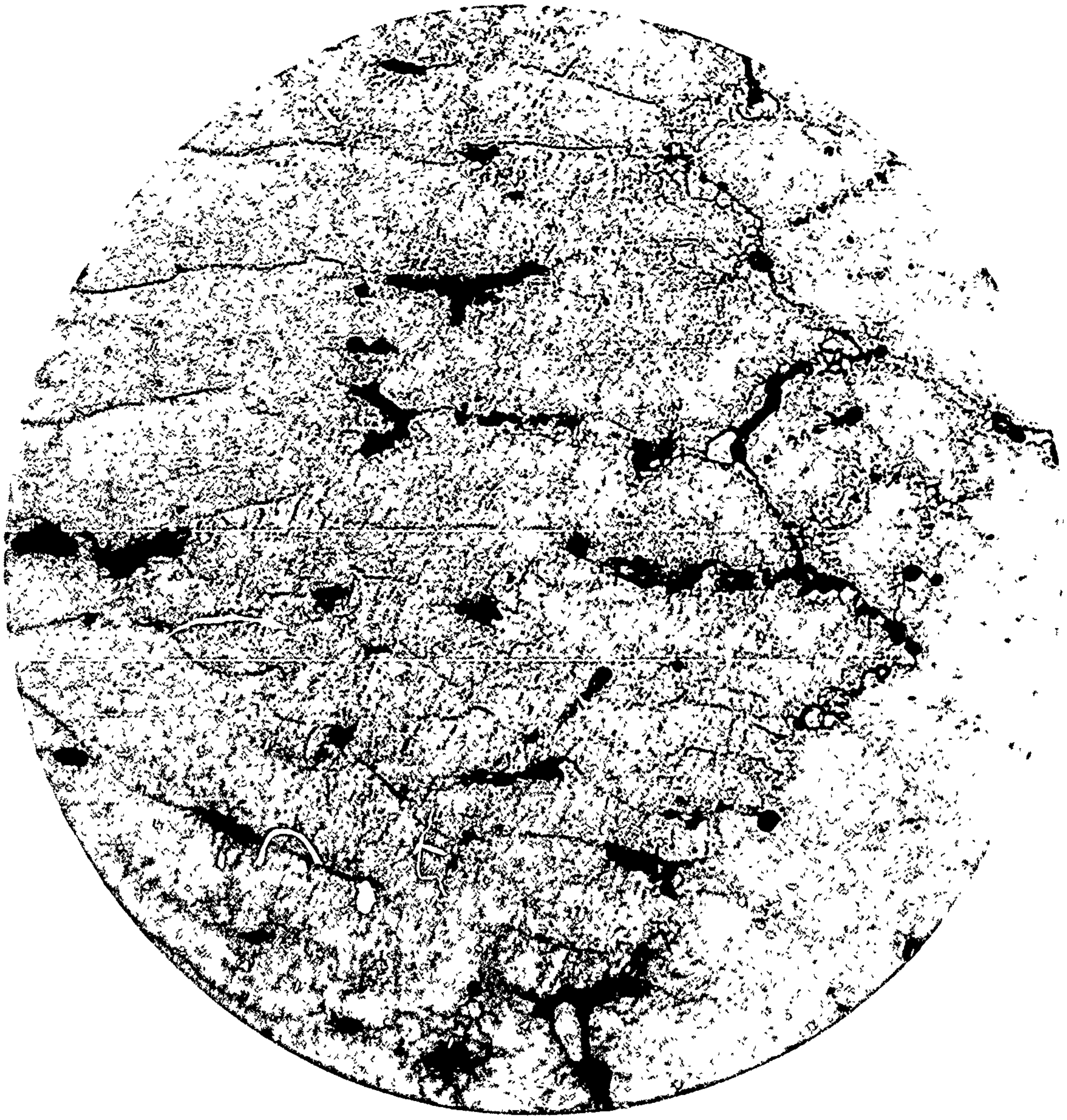
MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix with elongated grains showing the effect of rolling.

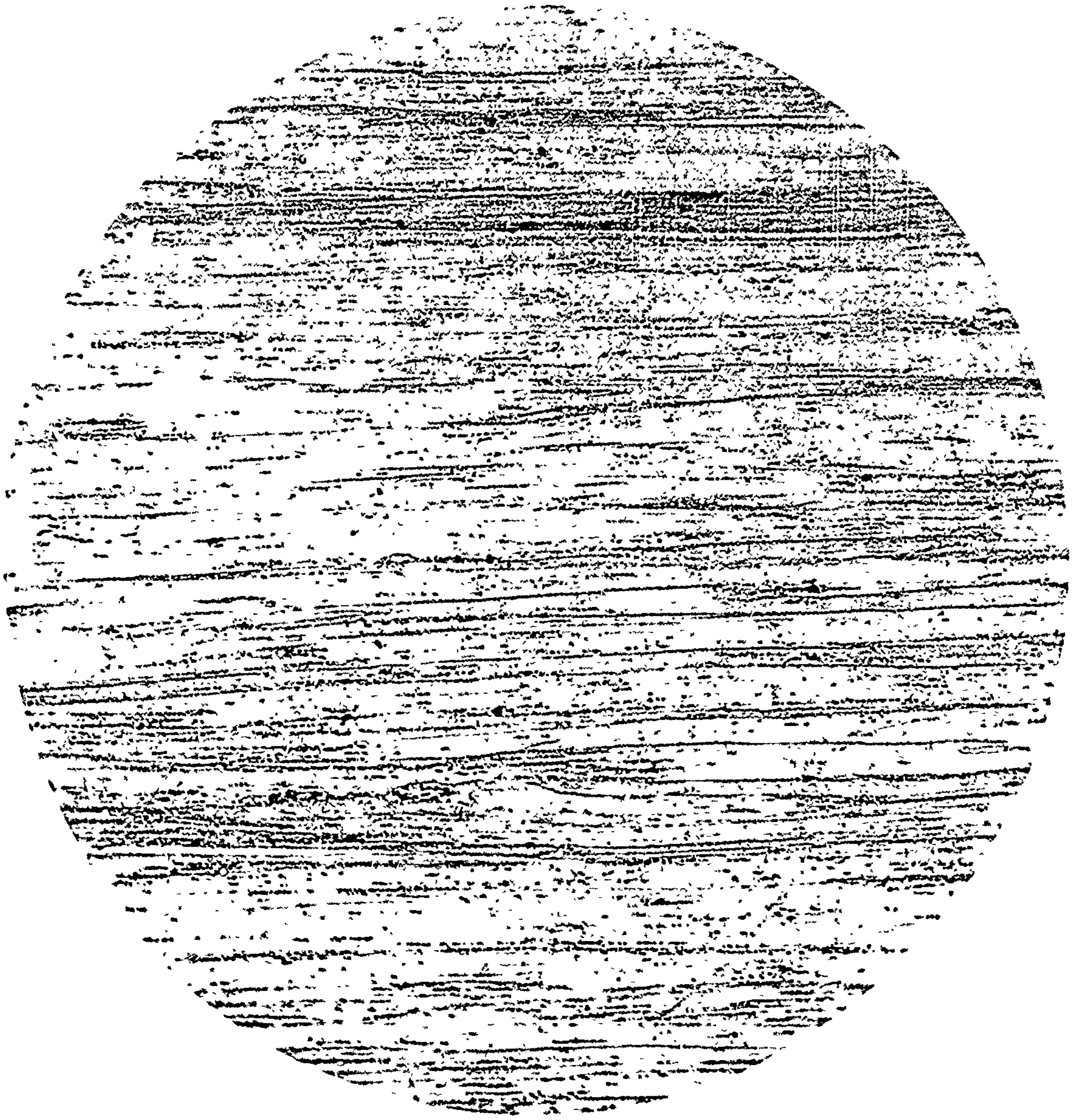
ALLO
PLATE: 1-1/
SECTION At center on plane parallel to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix showing a semi-continuous network of constituents laid down during freezing. The rolling operation has been unsuccessful in breaking up this structure.



of rolling.



ALLOY: 75S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane perpendicular to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix with elongated grains showing the effect of rolling.

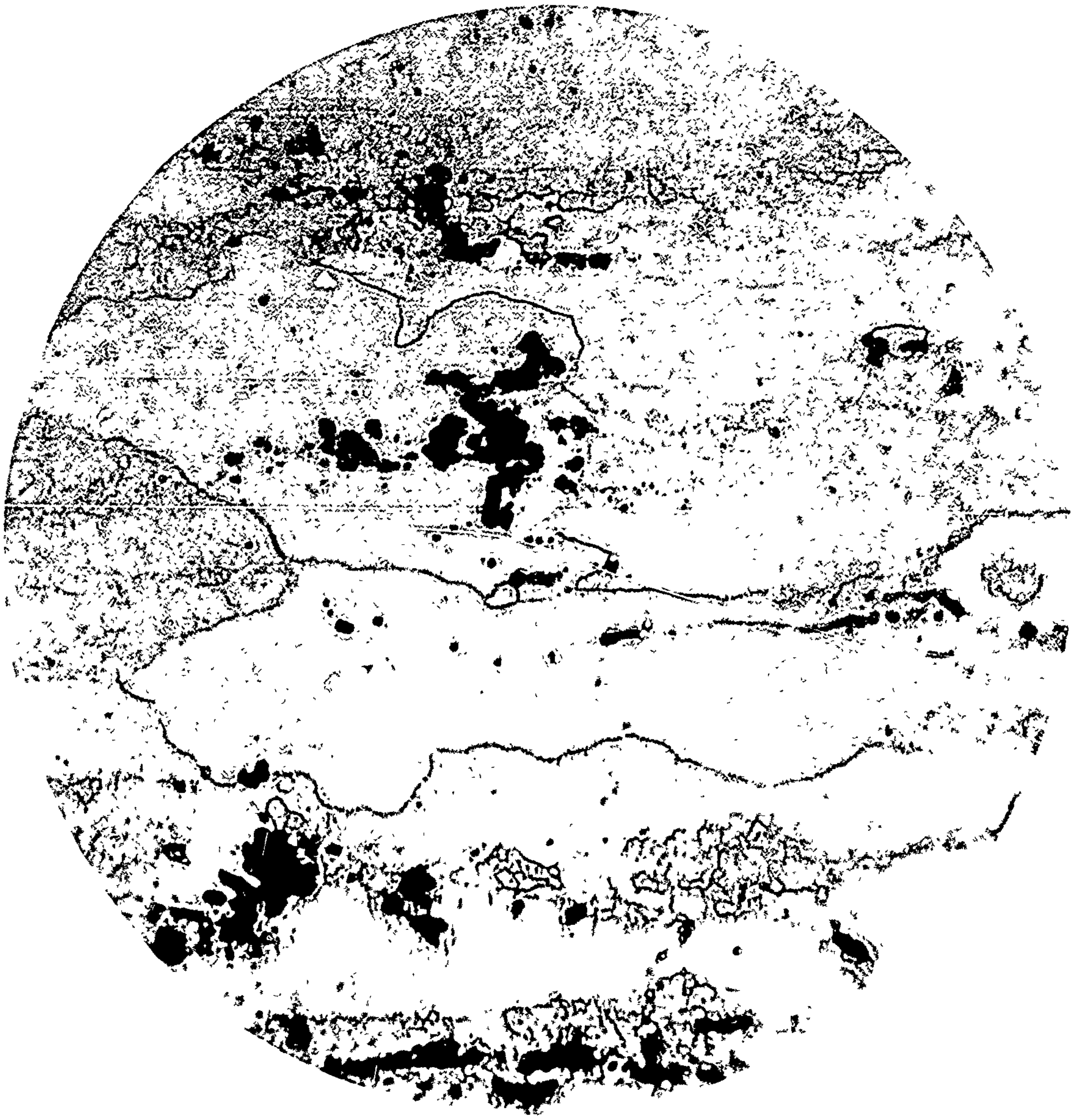
Aluminum alloy matrix showing a semi-continuous network of constituents laid down during freezing. The rolling operation has been unsuccessful in breaking up this structure.

ALLOY: 75S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 100X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix showing that the semi-continuous network of constituents visible in the 1-1/2" plate have been broken up by continued rolling.

Al-Zn-Cu-Mn constituents.



ALLOY: 75S-T ALCOA
PLATE: 3/4" GAUGE
SECTION: At center on plane parallel to surface.

MAGN: 500X ETCH: Kellers (.5% HF, 2.5% $HNO_3$, 1.5% HCl)

Aluminum alloy matrix showing scattered particles of Al-Zn-Cu-Mn constituents.